U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-251 621

Evaluation of Eight Novel Fine Particle Collection Devices

GCA Corp.

Prepared For
Industrial Environmental Research Lab.

February 1976

KEEP UP TO DATE

Between the time you ordered this report—which is only one of the hundreds of thousands in the NTIS information collection available to you—and the time you are reading this message, several *new* reports relevant to your interests probably have entered the collection.

Subscribe to the **Weekly Government Abstracts** series that will bring you summaries of new reports *as soon as they are received by NTIS* from the originators of the research. The WGA's are an NTIS weekly newsletter service covering the most recent research findings in 25 areas of industrial, technological, and sociological interest—invaluable information for executives and professionals who must keep up to date.

The executive and professional information service provided by NTIS in the **Weekly Government Abstracts** newsletters will give you thorough and comprehensive coverage of government-conducted or sponsored research activities. And you'll get this important information within two weeks of the time it's released by originating agencies.

WGA newsletters are computer produced and electronically photocomposed to slash the time gap between the release of a report and its availability. You can learn about technical innovations immediately—and use them in the most meaningful and productive ways possible for your organization. Please request NTIS-PR-205/PCW for more information.

The weekly newsletter series will keep you current. But *learn what you have missed in the past* by ordering a computer **NTISearch** of all the research reports in your area of interest, dating as far back as 1964, if you wish. Please request NTIS-PR-186/PCN for more information.

WRITE: Managing Editor
5285 Port Royal Road
Springfield, VA 22161

Keep Up To Date With SRIM

SRIM (Selected Research in Microfiche) provides you with regular, automatic distribution of the complete texts of NTIS research reports *only* in the subject areas you select. SRIM covers almost all Government research reports by subject area and/or the originating Federal or local government agency. You may subscribe by any category or subcategory of our WGA **(Weekly Government Abstracts)** or **Government Reports Announcements and Index** categories, or to the reports issued by a particular agency such as the Department of Defense, Federal Energy Administration, or Environmental Protection Agency. Other options that will give you greater selectivity are available on request.

The cost of SRIM service is only 45¢ domestic (60¢ foreign) for each complete microfiched report. Your SRIM service begins as soon as your order is received and processed and you will receive biweekly shipments thereafter. If you wish, your service will be backdated to furnish you microfiche of reports issued earlier.

Because of contractual arrangements with several Special Technology Groups, not all NTIS reports are distributed in the SRIM program. You will receive a notice in your microfiche shipments identifying the exceptionally priced reports not available through SRIM.

A deposit account with NTIS is required before this service can be initiated. If you have specific questions concerning this service, please call (703) 451-1558, or write NTIS, attention SRIM Product Manager.

This information product distributed by

NTIS U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

110172

PB 251 621

EPA-600/2-76-035
February 1976

Environmental Protection Technology Series

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY ·

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-76-035

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
Evaluation of Eight Novel Fine Particle Collection Devices

5. REPORT DATE
February 1976

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) Douglas W. Cooper, Richard Wang, and Daniel P. Anderson

8. PERFORMING ORGANIZATION REPORT NO.
GCA-TR-75-28-G

9. PERFORMING ORGANIZATION NAME AND ADDRESS
GCA Corporation
Burlington Road
Bedford, MA 01730

10. PROGRAM ELEMENT NO.
1AB012; ROAP 21ADL-004

11. CONTRACT/GRANT NO.
68-02-1316, Task 8

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Task Final; 2-11/75

14. SPONSORING AGENCY CODE
EPA-ORD

15. SUPPLEMENTARY NOTES
EPA project officer for this report is D. Harmon, 919/549-8411, Ext 2925.

16. ABSTRACT
The report summarizes IERL-RTP sponsored evaluations of eight novel control devices: Aronetics Two-Phase Jet Scrubber, Braxton Sonic Agglomerator, Centrifield Scrubber (Entoleter Corp.), Cleanable High Efficiency Air Filter (CHEAF, Johns-Manville), Dynactor Scrubber (RP Industries), Lone Star Steel Steam Hydro Scrubber, Mystaire (Heat Systems-Ultrasonics, Inc.), and Pentapure Scrubber (Purity Corp.). For each device is given a description, potential applications, theory of operation, collection efficiency (as a function of particle size), power consumption, and waste disposal techniques. Methods are detailed for comparing collection efficiencies and costs. The general theory of collection in scrubbers and by high porosity filters is presented to indicate the important parameters and their influence on collection efficiency.

Reproduced from
best available copy.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Agglomeration	Air Pollution Control	13B
Control Equipment	Efficiency	Stationary Sources	14B
Scrubbers		Novel Control Devices	07A
Filters		Particulate	
Acoustics		Fine Particles	20A
Collection		Sonic Agglomerators	

PRICES SUBJECT TO CHANGE

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 192
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE 7.50-2.25

EPA Form 2220-1 (9-73)

EPA-600/2-76-035
February 1976

EVALUATION OF EIGHT NOVEL FINE PARTICLE COLLECTION DEVICES

by

Douglas W. Cooper, Richard Wang,
and Daniel P. Anderson

GCA Corporation
Burlington Road
Bedford, Massachusetts 01730

Contract No. 68-02-1316, Task 8
ROAP No. 21ADL-004
Program Element No. 1AB012

EPA Project Officer: Dale L. Harmon

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

Presented are summaries of the evaluations sponsored by Industrial Environmental Research Laboratory - Research Triangle Park, of the following novel control devices: Aronetics Two-Phase Jet Scrubber, Braxton Sonic Agglomerator, the Centrifield Scrubber (Entoleter/Corporation), the Cleanable High Efficiency Air Filter (CHEAF, Johns-Manville), the Dynactor Scrubber (RP Industries), the Lone Star Steel Steam-Hydro Scrubber, the Mystaire (Heat Systems-Ultrasonics, Inc.), and the Pentapure Scrubber (Purity Corporation). For each device is given a description, potential applications, theory of operation, collection efficiency (as a function of particle size), power consumption and waste disposal techniques. Methods for comparing collection efficiencies and costs are detailed. The general theory of collection by scrubbers and by high porosity filters is presented to indicate the important parameters and their influence on collection efficiency. The appendix discusses the accepted definition of particle aerodynamic diameter.

CONTENTS

Page

Abstract iii

List of Figures v

List of Tables viii

Acknowledgments ix

Section

I Conclusions 1

II Recommendations 2

III Introduction 3

IV Aronetics Two-Phase Jet Scrubber 5

V Braxton Sonic Agglomerator 24

VI Centrifield Scrubber 38

VII Cleanable High Efficiency Air Filter (CHEAF) 48

VIII Dynactor Scrubber 55

IX Lone Star Steel Steam-Hydro Scrubber 75

X Mystaire Scrubber 91

XI Pentapure Scrubber 102

XII University of Washington Electrostatic Droplet Scrubber 115

XIII Efficiency Comparison 124

XIV Cost Comparison 136

XV Power Comparison 145

XVI Applications 149

XVII Collection Efficiency Theory 156

XVIII Appendix 176

XIX References 179

FIGURES

No.		Page
1	Generalized Two-Phase Jet Scrubber Nozzle	6
2	Generalized Two-Phase Jet Scrubber System	7
3	Variation of Water Droplet Velocity From Two-Phase Jet Nozzle With Water Temperature	8
4	System Pressure Rise as a Function of Water Flow Rate	10
5	Optical and Diffusional Sizing System	15
6	General Layout of Furnace and Scrubber System Showing Locations	16
7	Average Inlet Size Distribution on a Cumulative Weight Percentage Basis	19
8	Fractional Efficiency of the Aronetics Scrubber Based on Optical, Diffusional, and Inertial Sizing	20
9	Fractional Efficiency of the Aronetics Wet Scrubber Calculated From the Weighted Averages of 30 Inlet (Brink) and 6 Outlet (Andersen Mark II) Impactor Tests	21
10	Schematic Diagram of Test of Braxton Sonic Agglomerator	27
11	Collection Efficiencies Versus Aerodynamic Diameter for Cyclone, Agglomerator, and Cyclone Plus Agglomerator	31
12	Centripetal Vortex Balances Gas Velocity Against Centrifugal Force	39
13	Schematic Diagram of the Asphalt Plant and Scrubber Layout and the Locations of the Sampling Points Used in the Tests	44
14	Fractional Efficiencies as Determined by the Four Methods Used in the Test Program	45
15	Fractional Efficiencies of the Entoleter Centrifield Scrubber as Determined From Cascade Impactor Data	46
16	Diagram of CHEAF Installation	51
17	Collection Efficiency Versus Aerodynamic Diameter, CHEAF	52
18	Inlet and Outlet Cumulative Aerodynamic Diameter Distributions, CHEAF Tests	53

FIGURES (Continued)

No.		Page
19	Single-Stage Dynactor Diffusion System Cross Sectional View	56
20	Two-Stage Dynactor	58
21	Test System for Dynactor Two-Stage Scrubber Evaluation, Including Filter Samplers (F), Thermometers (T), and Pressure Gauge (P)	63
22	Details of Aerosol Concentration and Size Distribution Measurement Sections	64
23	Summary of Results of 16 Collection Efficiency Tests (Factorial Design)	68
24	The Lone Star Steel Steam-Hydro Air Cleaning System	77
25	Optical and Diffusional Sizing System	83
26	Inlet and Outlet Particle Size Distributions Measured Using Optical and Diffusional Techniques	85
27	Fractional Efficiency of the Lone Star Steel Steam-Hydro Scrubber	86
28	Collection Efficiency Versus Aerodynamic Diameter, Lone Star Steel Steam-Hydro Scrubber	87
29	Power Consumption Versus Flow Resistance for Lone Star Steel Steam-Hydro Scrubber	89
30	Schematic Diagram of the Mystaire Laboratory Scrubber	92
31	Estimated Mystaire Collection Efficiency Versus Particle Size	100
32	Schematic Diagram of Purity Corp. Impingement Scrubber, the Pentapure Scrubber	103
33	Schematic of Sampling Positions	106
34	Inlet Particle Size Distribution	108
35	Collection Efficiency Versus Aerodynamic Diameter, Data Means for Pentapure Scrubber	110
36	Data and Approximate Theory Predictions ($f = 0.25, 0.50$; $Q_L/Q_g = 0.57 \times 10^{-3}$) for Pentapure Scrubber	113

FIGURES (Continued)

No.		Page
37	Schematic Diagram of Electrostatic Droplet Scrubber	116
38	Calculated Particle Collection Efficiencies for a Single 200-μm Diameter Droplet With a 100-cm/s Undisturbed Fluid Velocity	121
39	Particle Collection Efficiency of Electrostatic Spray Droplet Scrubber as Function of Particle Size	122
40	Hypothetical Cumulative Mass Distribution (Log Normal, Mass Median = 1, Geometric Standard Deviation = 2)	125
41	Hypothetical Control Device Collection Efficiency Versus Particle Diameter	127
42	Treatment of Waste Waters to Effect Various Degrees of Contaminant Removal	141
43	Relationship Between Total Water Cost and Treatment	142
44	Collection Vehicle Hauling Costs	144
45	Predicted Aerodynamic Cut Diameter Versus Pressure Drop and Power Consumption (Adapted from Scrubber Handbook)	147
46	Criteria for Selection of Gas Cleaning Equipment	150
47	Geometry for Collector Analysis	157
48	Flow Streamlines and the Limiting Trajectories	163
48A	Combined Collection Efficiency Based on Experimental Results η_{ICD} Versus $(6Sc^{-2/3} Re^{-1/2} + 3Re^{1/2} R^2)$	168
49	Theoretically Calculated Migration Velocities for Four Electrostatic Mechanisms Versus Particle Diameter	171

TABLES

No.		Page
1	Weighted Average Inlet and Outlet Loadings, Aronetics Tests	18
2	Fractional Collection Efficiencies for the Braxton Sonic Agglomerator System, Cyclone, and Agglomerator/Cyclone Combination	30
3	Sonic Agglomerator System Operating Parameters	32
4	Comparison of Inlet and Outlet Dust Loading, Cyclone Catch, Cyclone Undersize Dust and Overall System Collection of All Particle Sizes	33
5	Summary of Results of 16 Collection Efficiency Tests for Dynactor (Factorial Test Design)	67
6	Efficiency Averages Versus Particle Aerodynamic Diameter	69
7	Significance of Effects of Flow, Dust, Temperature, and Concentration on Scrubber Collection Efficiency	70
8	Individual and Overall Particle Collection Efficiency Due to Impaction, Interception, and Diffusion	98
9	Mean Collection Efficiency, Impactor Data	109
10	Example of Calculation of Predicted Mass Collection Efficiency	129
11	Aerodynamic Cut Diameters for Several Novel Control Devices	132
12	Average Fine Particle Efficiencies for the Novel Control Devices	134
13	Power Consumption Figures for Novel Control Devices Evaluated for IERL-RTP	146
14	Advantages and Disadvantages of Collection Devices	152
15	Advantages and Disadvantages of Wet and Dry Collectors	153
16	Industrial Process and Control Summary	155
17	Calculated η_I Compared With Data	166
18	Approximate Particle Charge (Cochet Equation) (Conducting Particles; E = 10 kV/cm = 33.3 esu)	170

ACKNOWLEDGMENTS

This work has been facilitated by the cooperation of the other organizations which made the original evaluations: Southern Research Institute, Midwest Research Institute, and Air Pollution Technology, Inc. The Project Officer, Dale Harmon, was instrumental in obtaining the materials which were central to this report. This help is gratefully acknowledged.

SECTION I

CONCLUSIONS

The novel control devices evaluated for the Industrial Environmental Reseach Laboratory - Research Triangle Park, of the Environmental Protection Agency displayed a wide range of efficiencies and power consumption rates. Not all were capable of 90 percent or better collection efficiency on particles smaller than 3 μm, an approximate criterion for being a high efficiency collector of fine particulates. Most of the novel control devices were related to the spray scrubber, including two which utilized waste heat for improved scrubbing efficiency and one which added electrostatic forces to the collection mechanisms. Two of the novel devices were essentially wetted filters, with the cleaning being done by the flow of water rather than by mechanical dislodgement. In comparing the novel devices with each other and with conventional control devices, one must consider the collection efficiency needed and the efficiency attainable; a rational economic decision involves comparison of the devices on the basis of total annualized cost, where possible.

SECTION II

RECOMMENDATIONS

The primary goal of this work was to present, rather than evaluate, the results of the novel control device evaluations sponsored by the Industrial Environmental Research Laboratory - Research Triangle Park. The prospective user of particulate control equipment should determine the nature of the particulate he must control with regard to its chemical nature and particle size distribution, and the nature of the gas in which it is borne, especially its actual and standard flow rates, its temperature, and its chemical composition. From those novel or conventional control devices which would be suited to his requirements, the user can choose among them on the basis of their collection efficiencies and total annualized costs, methods for doing both of which are indicated herein, in Sections XIII to XVI on efficiency, power, cost, and applicability.

SECTION III

INTRODUCTION

As one of its approaches to the reduction of the emission of fine particulates (those with diameters smaller than about 3 μm), the Industrial Environmental Research Laboratory - Research Triangle Park of EPA has sponsored the evaluation of a number of control devices presented by their designers as having important novel features in comparison with conventional technology (filters, scrubbers, electrostatic precipitators). These evaluations were of two general types: primarily theoretical or primarily experimental. Only the Mystaire and the University of Washington scrubber were of the former, nonexperimental type of evaluation. Presented here are synopses of these evaluations, along with methods for comparing efficiencies, costs, power consumption, and applicability.

The devices are presented in alphabetical order, by the name usually associated with them. The principal features of the devices are as listed below:

- Aronetics Scrubber - uses waste heat to produce a high energy spray which cleans and moves the gas.
- Braxton Sonic Agglomerator - employs high energy sound to agglomerate fine particles on droplets and on coarser particles, thus facilitating their removal by low-energy collectors such as cyclones.
- Centrifield Scrubber - creates vortex flow to improve the collection efficiency of its spray.
- Cleanable High Efficiency Air Filter - produces collection efficiencies on the order of 95 percent with a porous medium that is continually cleaned by water.

- Dynactor Scrubber - incorporates a proprietary nozzle design to enhance collection efficiency in a spray scrubber that cleans and moves the gas.
- Lone Star Steel Scrubber - uses waste heat to produce steam to drive a scrubber similar to a venturi scrubber, producing efficiencies higher than 99 percent for particles larger than about 0.3 μm, and providing motive power to the gas.
- Mystaire Scrubber - combines spray scrubbing and filtration to produce particle collection on wetted wire mesh, which is cleaned by a combination of spray flow and cross-current water flow.
- Pentapure Scrubber - produces particle agglomeration and collection on spray droplets by passing the gas/droplet/particle mixture through a converging section which directs the mixture jet at a collecting target.
- University of Washington Electrostatic Spray Droplet Scrubber - adds electrostatic force collection to the usual collection mechanisms in spray scrubbing to improve collection efficiency at a given level of power consumption.

The individual device summaries are followed by sections showing how to estimate efficiencies for a particular dust given the control device efficiency curves; how to compare cost and power consumption; the typical applications for devices similar to either filters, scrubbers, or electrostatic precipitators; the underlying theory of particle collection on obstacles, which is relevent for these scrubber-type or filter-type collectors; and an appendix on the definition of the particle aerodynamic diameter, a term frequently used in particulate material control technology.

SECTION IV

ARONETICS TWO-PHASE JET SCRUBBER

MANUFACTURER'S DESCRIPTION[1]

"A pressurized, heated liquid when passed through a properly designed nozzle will produce a two-phase mixture of vapor and liquid droplets that is an excellent cleaning medium. The droplets can be accelerated to extremely high velocity as a result of the expansion force created by a portion of the liquid being converted to vapor. The general configuration of this type of scrubber is shown in Figures 1 and 2. The proper arrangement of components allows a draft to be induced which eliminates or drastically reduces fan power requirements. The two-phase jet scrubber produces water droplet velocities which vary with the temperature of the scrubbing fluid as shown in Figure 3. It is Aronetic's experience that jet velocities in the range of 1000 feet per second are quite satisfactory for particulate removal in the size range down to 0.10 microns. The velocity in the region immediately downstream of the nozzle is probably substantially supersonic since there is considerable evidence that sonic velocity in a two-phase mixture may be as low as 350 feet per second. However, Aronetics believes that inertial impaction is the controlling mechanism in cleaning and that the existence, or absence, of the shock phenomena associated with supersonic flow is not an advantage in the cleaning effectiveness. Thus, the velocity in feet per second is the controlling parameter rather than the Mach number, or relationship of velocity to the local speed of sound. The device operates at a very low noise level. The sound frequency and level is similar to that generated by a garden hose nozzle.

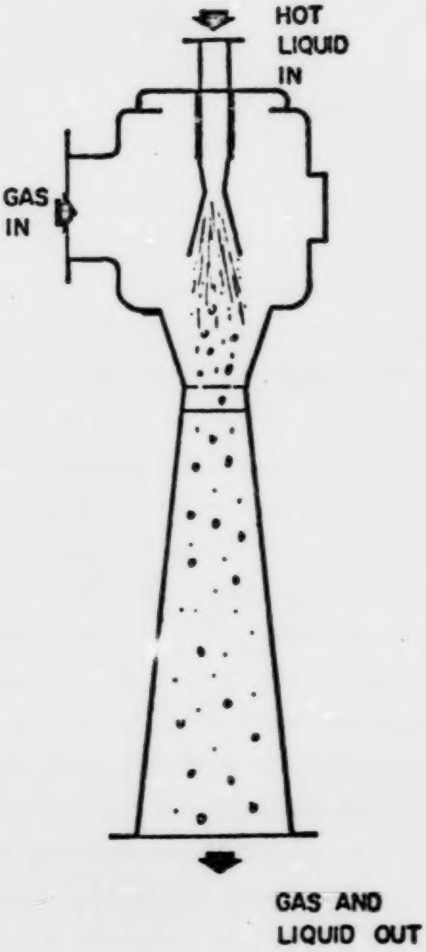

HOT
LIQUID
IN
GAS
IN
GAS AND
LIQUID OUT

Figure 1. Generalized two-phase jet scrubber nozzle

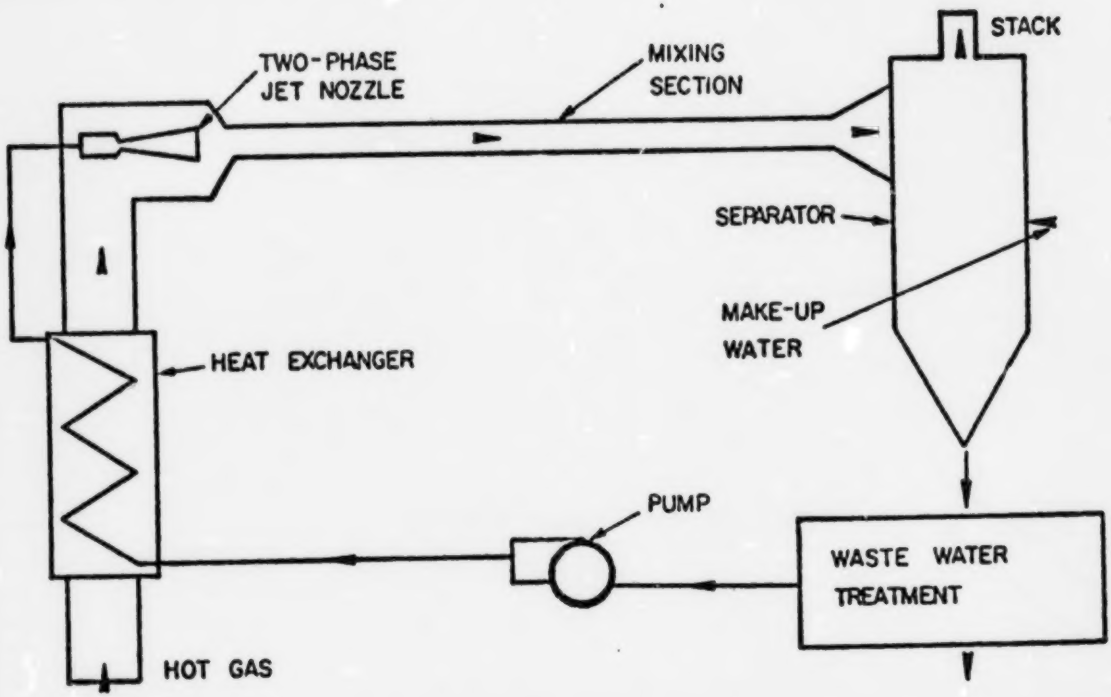

TWO-PHASE
JET NOZZLE
MIXING
SECTION
STACK
SEPARATOR
MAKE-UP
WATER
HEAT EXCHANGER
PUMP
WASTE WATER
TREATMENT
HOT GAS

Figure 2. Generalized two-phase jet scrubber system[1]

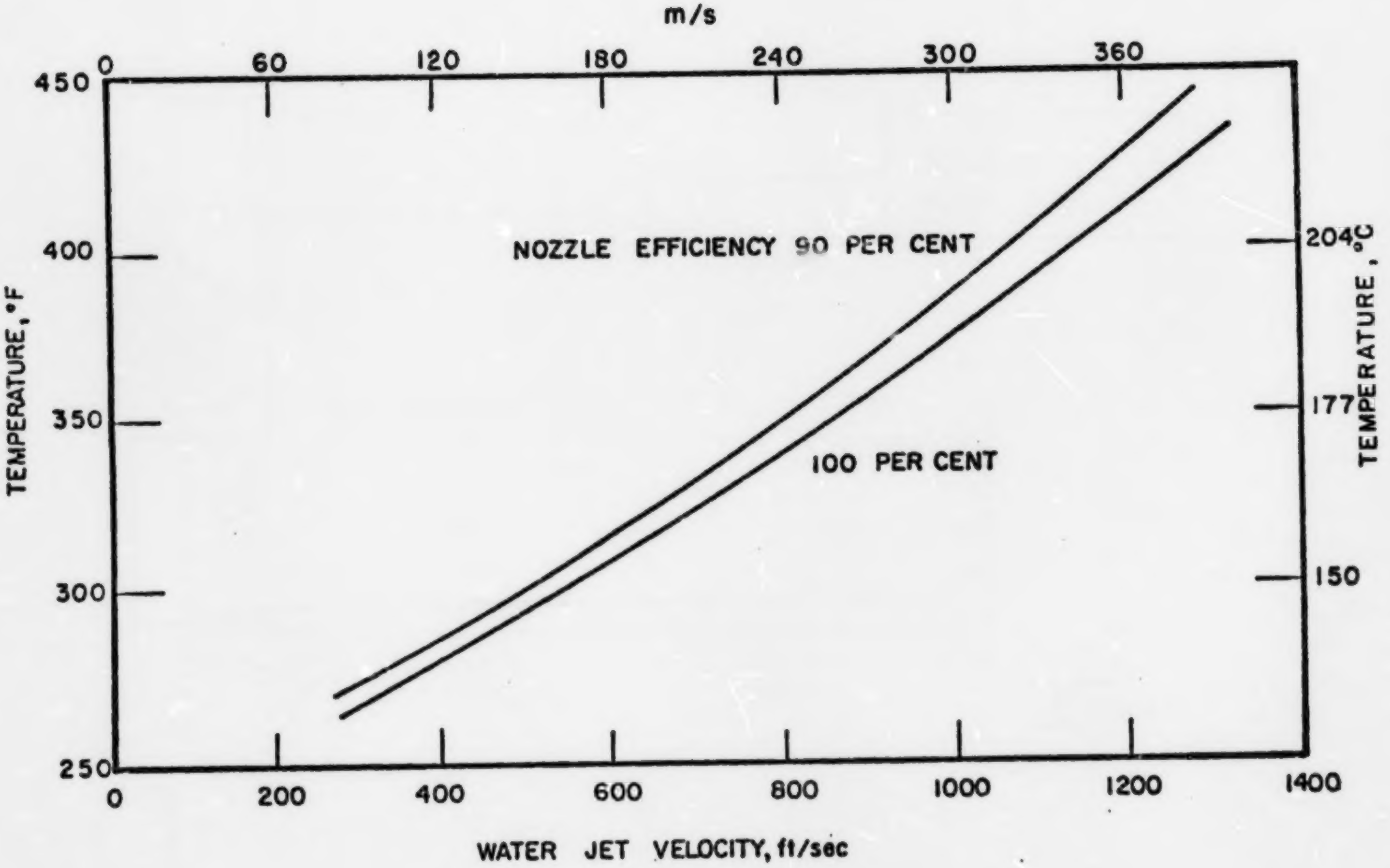


Figure 3. Variation of water droplet velocity from two-phase jet nozzle with water temperature[1] (metric units added)

"With respect to the draft producing capacity of this type of scrubber system, it should be evident that this is a pure momentum transfer mechanism; therefore, the amount of draft is a function of the amount of fluid passed through the nozzle and the degree to which this fluid is accelerated. The velocity is a function of initial water temperature, as shown in the previous figure. The effect of water flow rate on system pressure rise is shown in Figure 4 for water at a temperature of 400°F. It should be emphasized that this is a rise in pressure across the scrubber and should not be confused with the pressure drop which is associated with the venturi type scrubber. In most applications, the pressure rise produced by the two-phase jet is sufficient to overcome the pressure drop in other components of a complete system.

"The most direct application of the two-phase scrubbing system is in the control of emissions from processes which generate high temperature gas, laden with submicron particulate. Typical examples are the various metallurgical furnaces and processes. Figure 2 showed schematically the general arrangement of the components as tested in this report. An economizer type of heat exchanger is used to transfer thermal energy from the high temperature process exhaust gas to pressurized hot water which is delivered to the heat exchanger by a pump. Water exiting the heat exchanger is delivered directly to the nozzle in its liquid state. For most applications, the water temperature is approximately 400°F and the water pressure is approximately 350 psi, or high enough to ensure that the fluid remains in the liquid state until it has passed the nozzle throat. A properly dimensioned mixing section must be provided for intimate contact between the accelerated water droplets and the particle laden gas. The final component in the scrubbing system train is a separator which will remove the dirty water droplets and allow the clean gas to be discharged. Water drained from the separator is passed to water treatment equipment which may be used to remove substances scrubbed

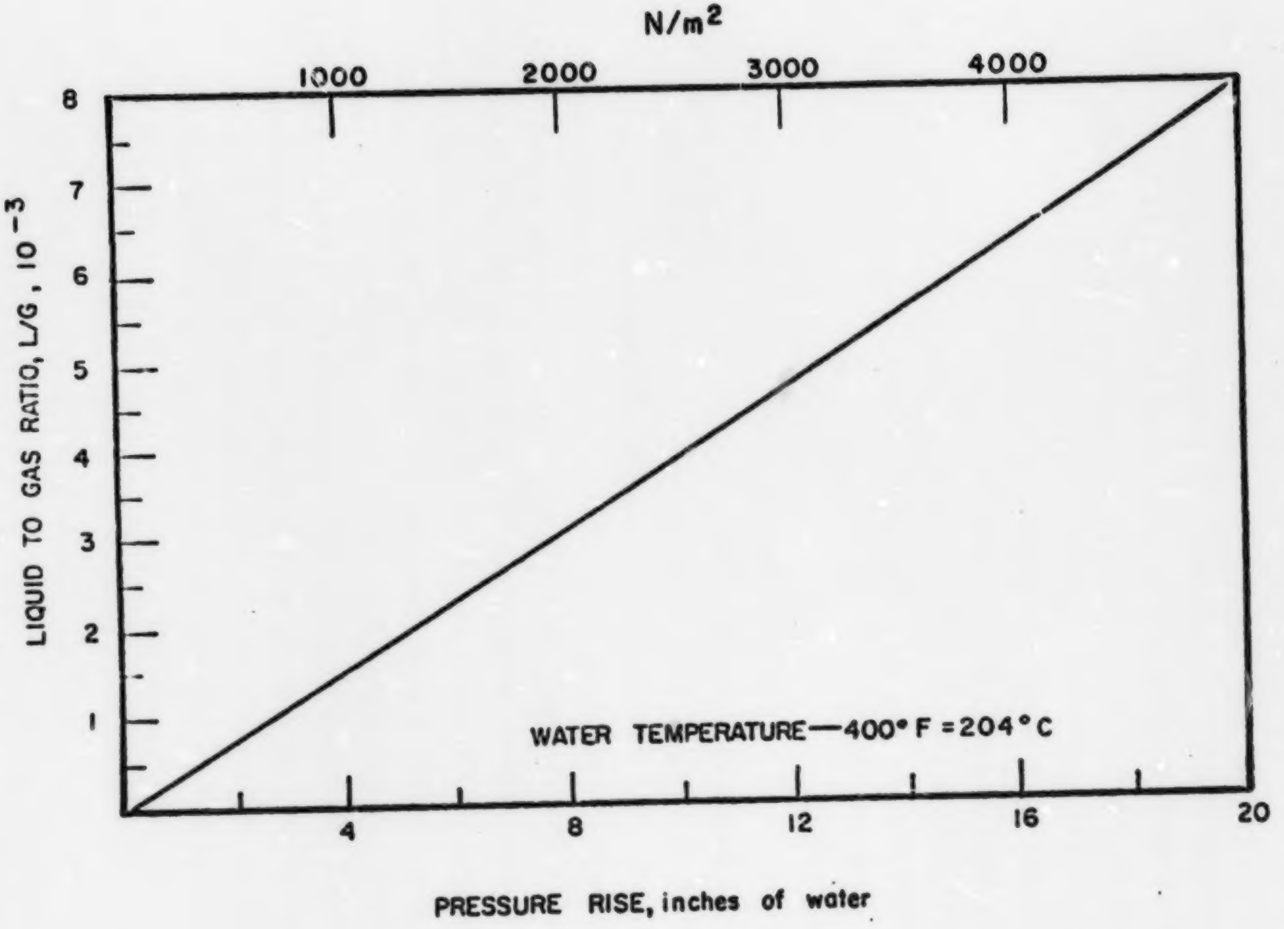


Figure 4. System pressure rise as a function of water flow rate (metric units added)

from the gas and to prepare the scrubbing liquid for recycling. In the present instance, the water is used for approximately three passes through the system before final discharge.

"If the process off-gas is at a temperature level above 1200°F, an additional option becomes available in the selection of components. The economizer type of heat exchanger may still be used to deliver heated water directly to the nozzle, or a steam boiler may be used as an intermediate step in the heating of water. If sufficient energy is contained in the gas, it is possible that a quantity of steam may be produced which is greater than the demands of the scrubber. This steam is then available for other possible plant applications. Other elements of the system remain essentially the same with the exception of the addition of a method to transfer thermal energy from steam to water. The choice between the steam boiler and the economizer type of system for the very high temperature gases is dictated by local conditions at the site in question."

POTENTIAL APPLICATIONS

This scrubber would be applicable to situations in which other high-energy scrubbers are logical candidates such as steel mills, foundries, refineries, paper mills, and industries with sticky or liquid emissions. It is substantially more economical if waste heat is available than it would be without waste heat. It is now manufactured by Chemical Air Pollution Control Co. of New York City.

Particle Characteristics

Particle Size - Collection efficiency was found to be greater than 50 percent for particles larger than 0.15 μm aerodynamic diameter, greater than 90 percent for particles larger than 0.3 μm aerodynamic diameter, and greater than 99 percent for particles larger than about 1 μm aerodynamic diameter. (See Appendix for definition of aerodynamic diameter.)

Particle Phase - The scrubber should be capable of removing solid or liquid aerosol particles.

Particle Resistivity - Scrubbing action should be independent of resistivity.

Particle Abrasiveness - Because the design produces high relative velocities between particles and drops without producing high gas velocities, abrasion should be less a problem than for a venturi scrubber.

Gas Characteristics

Volume Rate of Flow - Because the relative velocity between drops and particulate pollutants is produced by the nozzle rather than by the gas, changes in volume flow rate should not have as much effect upon collection efficiency as for constant-throat venturi scrubbers.

Gas Temperature - Higher gas temperatures mean that the gas is more viscous, thus making particle collection by impaction somewhat more difficult. This is overbalanced by the advantage of having available waste heat to drive the scrubber. Sufficient heat must be available to raise the water temperature in the scrubber to near the 204°C (400°F) design value. The manufacturer suggests using an economizer for temperatures less than 650°C (1200°F), noting that in the range 650 to 2200°C (1200°F to 4000°F) gas temperature it may be advantageous to use a steam boiler to generate steam, only part of which would be needed for the scrubber.

THEORY OF OPERATION

The mechanisms by which particles are captured by the high-speed spray are those discussed in Section XVII on collector theory. The water will generally be at a lower temperature than the stack gas, which means that thermophoresis will be a force for collection of particles; evaporation from the droplets will tend to reduce their collection efficiency, however. The data below are consistent with the hypothesis that impaction predominates for particulate matter as small as a few tenths microns, and diffusive collection predominates for the particles still smaller.

The generation of the spray is described in the manufacturer's description at the beginning of this section. The droplets are accelerated through the nozzle by the pressure in the tank, and then accelerated still more by the evaporation/disintegration process that occurs due to the high vapor pressure of the water at 200°C (400°F) or more. The resulting kinetic energy is the product of the nozzle efficiency factor and the change in enthalpy of the steam/water mixture, the two-phase flow. Calculations by the developers indicate drop velocities of about 300 m/s (1000 ft/s) are attained. If the droplets were roughly 100 μm in diameter, a typical value for other scrubbers that use different atomization techniques, then impaction could well be important even for particle diameters of 0.2 μm.

The droplets and the particulate matter captured by them are collected in the cyclone that is part of the system. Particles on which water has condensed may also become sufficiently massive to be collected in the cyclone.

Gas flow is induced by the two-phase flow from the nozzle, so no fans are required, but the pressure in the heating section is 2.3×10^6 N/m^2, (350 psi) and this must be maintained by a pump.

COLLECTION EFFICIENCY

The particle concentrations in various size intervals for measuring the efficiency as a function of particle size were determined by three different methods by Southern Research Institute.[1] For particles with aerodynamic diameters between 0.3 and 5 μm, cascade impactors were used. For particles with sizes less than 1 μm, an optical particle counter (aerosol photometer) and the combination of diffusion battery and condensation nuclei counter (CNC) were used.

The optical and diffusional system shown in Figure 5 included a diffusion battery for size distribution, a condensation nuclei counter for concentration and an optical counter for particle size and concentration, with a dilution device which reduces the concentrations by a factor of about 10^2 and diffusional driers to eliminate water condensation effects.

Due to its complexity, only one set of equipment was available. The data for the inlet and outlet were obtained in two separate attempts with the assumption that the furnace process was sufficiently repetitive.

The total mass concentrations for the inlet and outlet were sampled by conventional (EPA Method 5) techniques. The locations for sampling systems and the general layout of furnace and scrubber system are presented in Figure 6.

The tests were conducted at a 7.5 MW submerged arc ferro-alloy furnace at Chromasco, Inc.'s, Memphis, Tennessee facility, which operates continuously, producing around 31 metric tons/day of ferrochrome. The operations for a batch cycle are: charging, stoking, normal operation, and tapping, within a nominal 120 minutes period. The emission rates vary throughout the cycle, and this causes some difficulty in measurement and interpretation. However, the trends in the fractional efficiencies and the fractions of the influent material that penetrate the scrubber are estimated by the experimentors to be reliable to within a factor of two.[1]

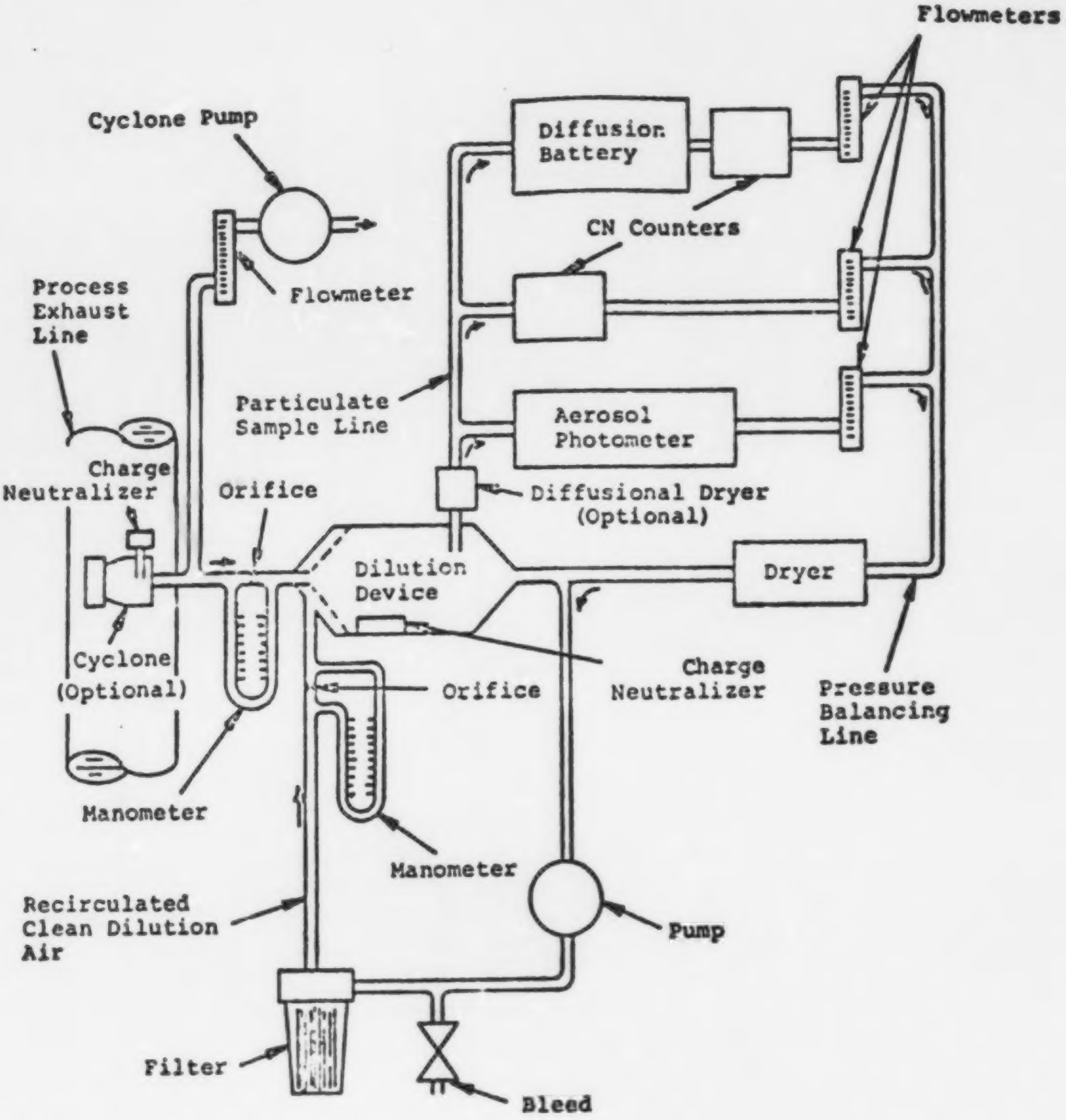

Flowmeters
Cyclone Pump
Diffusion Battery
CN Counters
Flowmeter
Process Exhaust Line
Particulate Sample Line
Aerosol Photometer
Charge Neutralizer
Orifice
Diffusional Dryer (Optional)
Dilution Device
Dryer
Cyclone (Optional)
Charge Neutralizer
Orifice
Pressure Balancing Line
Manometer
Manometer
Recirculated Clean Dilution Air
Pump
Filter
Bleed

Figure 5. Optical and diffusional sizing system[1]

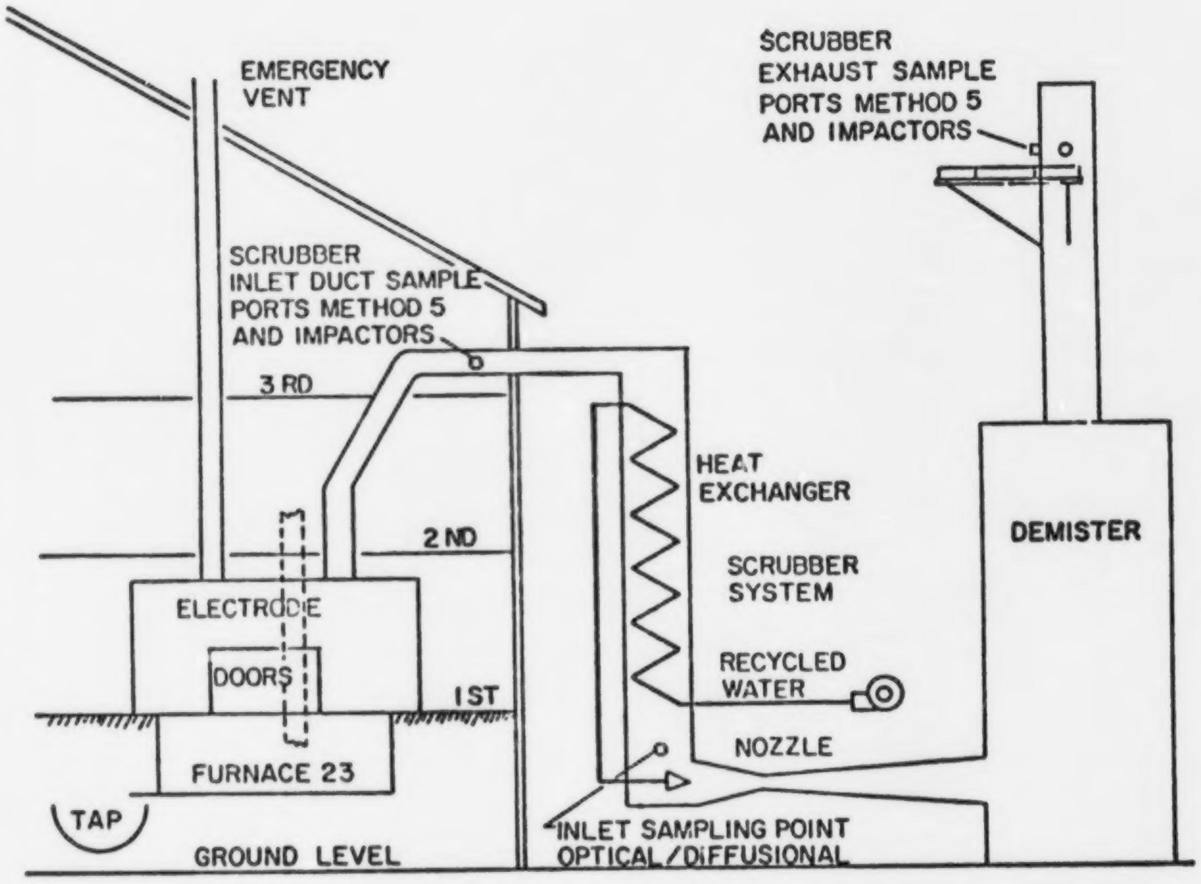

SCRUBBER
EXHAUST SAMPLE
PORTS METHOD 5
AND IMPACTORS
EMERGENCY
VENT
SCRUBBER
INLET DUCT SAMPLE
PORTS METHOD 5
AND IMPACTORS
3 RD
2 ND
1 ST
ELECTRODE
DOORS
FURNACE 23
TAP
GROUND LEVEL
HEAT
EXCHANGER
SCRUBBER
SYSTEM
RECYCLED
WATER
NOZZLE
INLET SAMPLING POINT
OPTICAL/DIFFUSIONAL
DEMISTER

Figure 6. General layout of furnace and scrubber system showing locations[1]

The general configuration for the scrubber system has been shown in Figure 2.

Waste gas at 590°C (1095°F) passing through the heat exchanger brings up the water temperature from 43°C (109°F) to 207°C (404°F). The gas leaves the heat exchanger at 104°C (219°F). Water at 207°C (404°F) and 24×10^5 N/m^2 (350 psi) jets out of the nozzle and meets the gas stream in the mixing tube. The resulting spray jet acts as a fan to produce the draft for the entire furnace and scrubber system. The unevaporated droplets collect particulates and enter the separator, from which clean air leaves at 62°C (143°F) and water with captured particulate goes into treatment section for recycling or discharging.

Because of the relatively small duct dimensions and the relatively fine particulate being sampled, single point sampling was used, at isokinetic conditions.

Inlet and outlet mass loadings were different by from about 50:1 to 380:1. Therefore, it took 8 hours sampling time for outlet and about 5 minutes for inlet. The weighted average for all runs corresponding to each size interval for both inlet and outlet are shown in Table 1. Figure 7 (from the SoRI report) shows the average inlet particulate size distributions on a cumulative basis. (That is, the graph is total concentration smaller than a given diameter.) In Figure 8 (again from SoRI) the inlet and outlet concentration data have been used to obtain collection efficiency as a function of particle diameter. The diameters used were equivalent diameters; for optical sizing, the diameter of a polystyrene sphere giving the same light scattering; for the impactor sizing, the diameter of a sphere of density 4.5 g/cm^3. The impactor data were also presented by SoRI in terms of efficiency as a function of aerodynamic diameter, in Figure 9, a useful presentation for those who would extrapolate these results to particulate material of another density. The aerodynamic diameter at which the efficiency was 50 percent was roughly 0.3 μm, obtained by correcting the

Table 1. WEIGHTED AVERAGE INLET AND OUTLET LOADINGS, ARONETICS TESTS

Inlet									
Size interval (μm)	<0.5	0.5 -1.2	1.2 -1.6	1.6 -3.0	3.0 -4.3	4.3 -7.2	7.2 -13	>13	
Loading (mg/DSCM)[a]	91.5	75.5	57.2	34.3	27.5	29.7	61.8	199	
Outlet									
Size interval (μm)	<0.67	0.67 -0.92	0.92 -1.5	1.5 -3.2	3.2 -4.9	4.9 -6.9	6.9 -11.1	11.1 -15.8	>15.8
Loading (mg/DSCM)	5.56	0.92	0.62	0.43	0.33	0.28	0.29	0.28	0.39

[a] Mg per dry standard cubic meter.

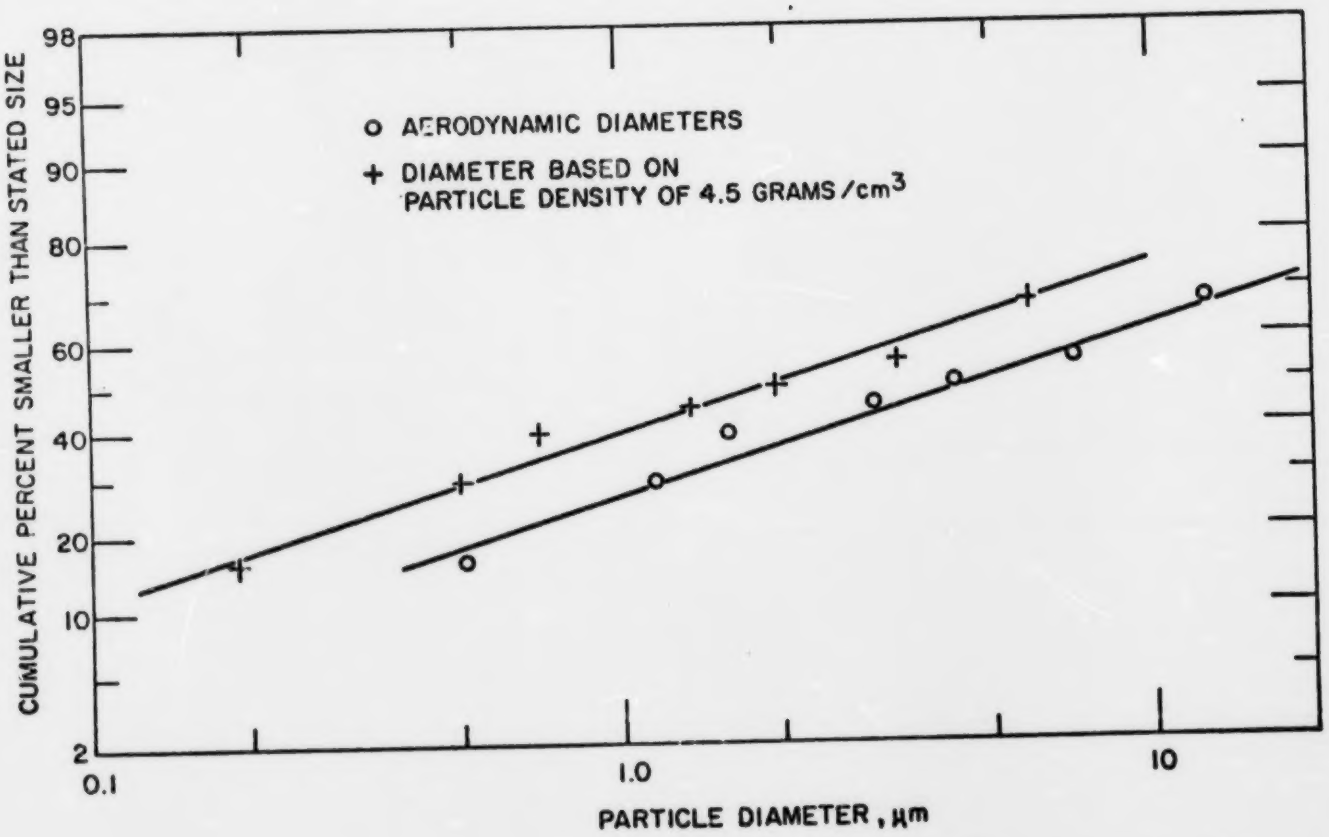


Figure 7. Average inlet size distribution on a cumulative weight percentage basis

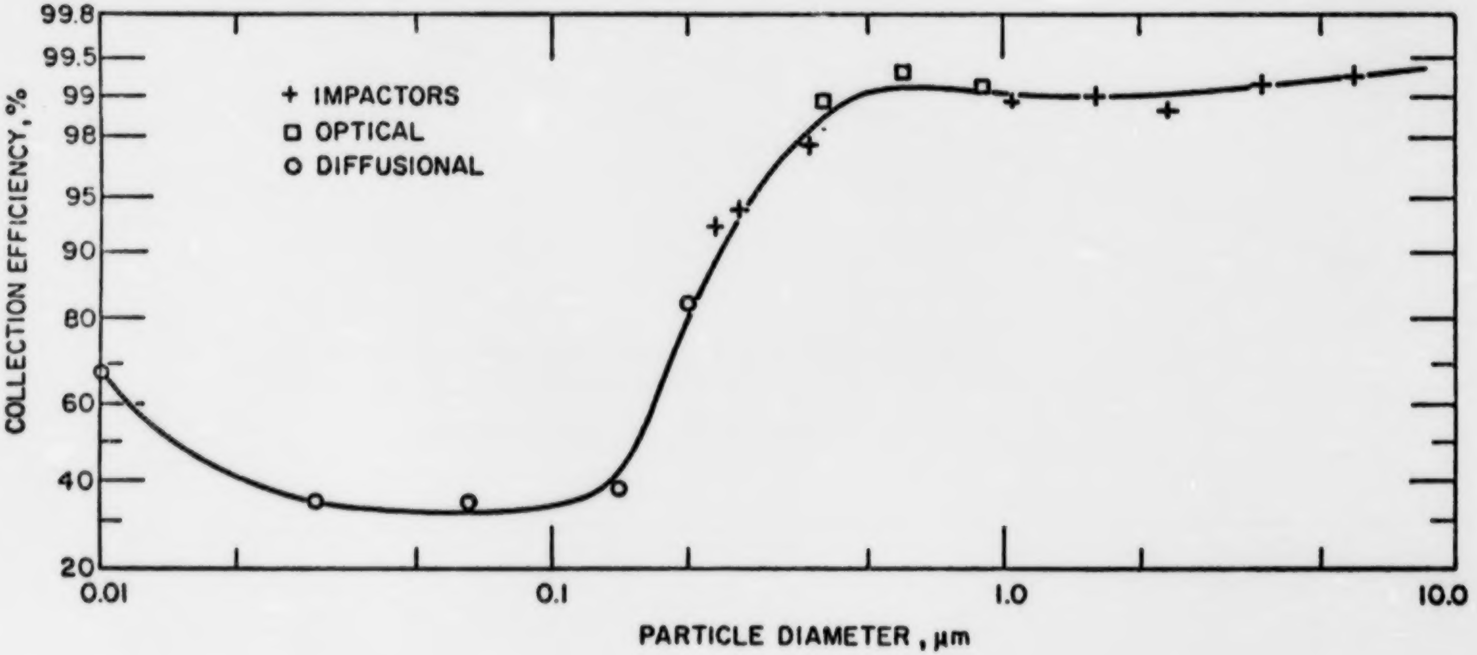


Figure 8. Fractional efficiency of the Aronetics scrubber based on optical, diffusional, and inertial sizing;[1] using equivalent diameters

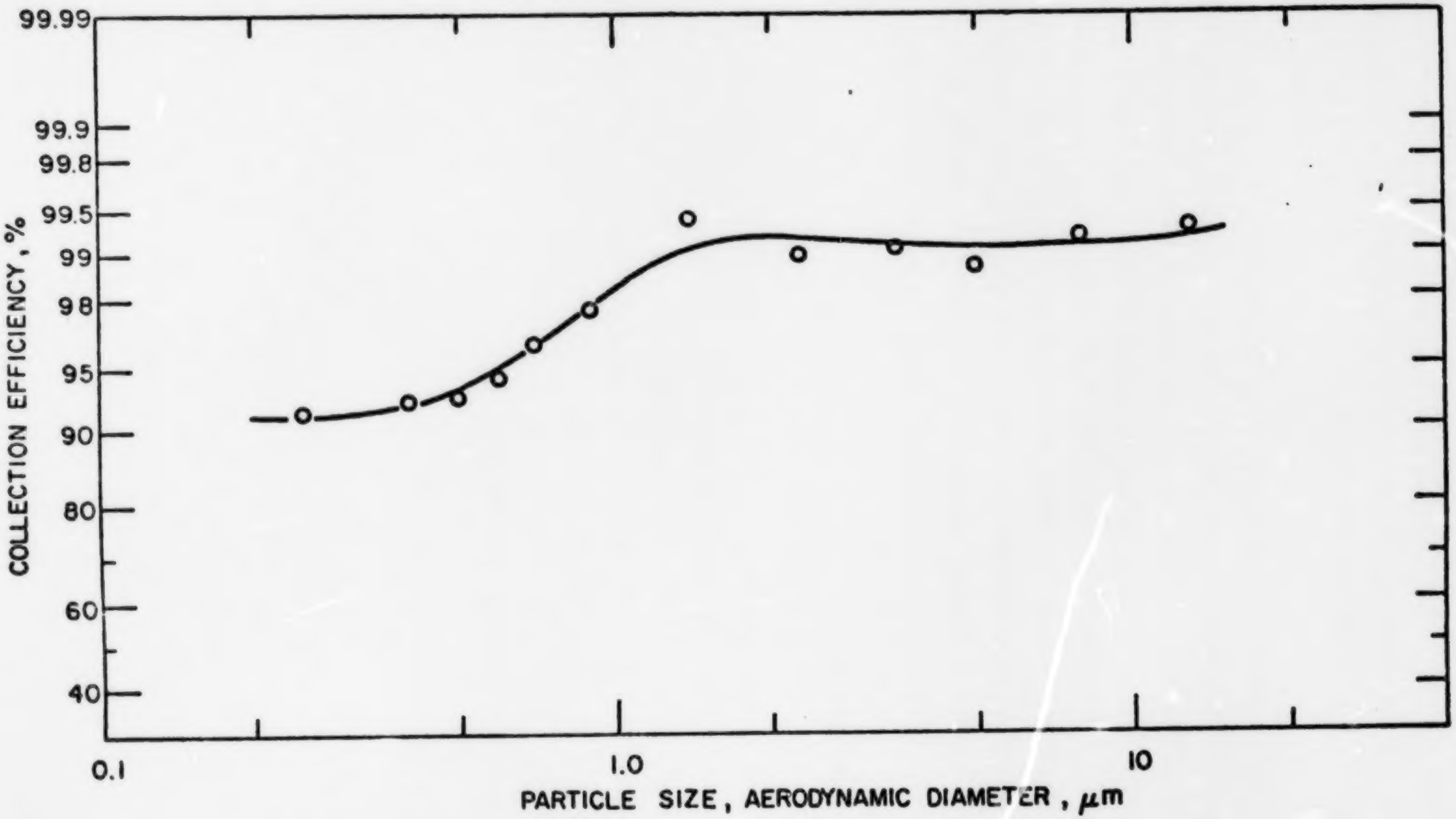


Figure 9. Fractional efficiency of the Aronetics scrubber calculated from the weighted averages of 30 inlet (Brink) and 6 outlet (Andersen Mark II) impactor tests. Particle sizes are given as aerodynamic diameters (density = 1 gm/cm^3).[1]

mobility diameter for 50-percent efficiency, 0.15 μm, by the square root of the particle density to yield the approximate aerodynamic diameter of the 0.15 μm diameter particles.

Total mass collection efficiencies were obtained by Guardian Systems, Inc., under subcontract to SoRI. Average efficiencies were 95.1 percent for this dust, which has a mass mean diameter near 3 μm and a mass mean aerodynamic diameter of about 6 μm. (See Figure 7.) The geometric standard deviation appears to have been approximately 10, so that there was a very substantial fraction (~30 percent) of the particulate mass contained in particles with geometric diameters smaller than 1/2 micron, which are often very difficult for particulate pollution control systems to remove from the gas stream.

POWER CONSUMPTION

The scrubber uses power from two sources: electrical energy to drive the pump which supplies water to the heater and thermal energy from the gas to provide the temperature increase in the water heater. If the latter is obtained from heat normally wasted, then in a sense it does not count as power consumption.

The power, P, consumed by the pump is

$$P = Q_L \, \Delta p_L / \eta$$

where P = power, watts
Q_L = liquid volume flow rate, m^3/s
Δp_L = liquid pressure, N/m^2
η = pump mechanical efficiency, 0.6.

For air flows of 0.47 m^3/s (1000 cfm), 26.5×10^{-3} m^3/min (7.0 gal/min) water spray is needed; the pressure drop was 2.41×10^6 N/m^2, so

$$P = \left((26.5/60) \times 10^{-3}\ m^3/s\right) \left(2.41 \times 10^6\ N/m^2\ /0.6\right)$$

$$P = 1.78\ kW = 2.38\ hp.$$

The intrinsic power (not including pump efficiency) is 1.43 hp/1000 cfm or 2.27 kW/(m^3/s) or 23 cm WC equivalent pressure drop for the gas flow.

The waste heat power used P_{wh} can be obtained from the product of the gas heat capacity, the gas mass flow rate and the change in temperature of the gas in going through the boiler. Southern Research Institute calculated this to be 17,000 Btu/1000 cfm which is 400 hp/1000 cfm or 630 kW/(m^3/s).

SUMMARY

The Aronetics spray scrubber produces particle collection and gas motion by a spray which derived its power from pumping and waste heat recovery. The test results obtained by SoRI can be used with the efficiency and cost comparison methods of SectionsXIII and XIV as part of an engineering analysis of applicability (Section XIV).

SECTION V

BRAXTON SONIC AGGLOMERATOR

DESCRIPTION

The 7 m^3/s (15,000 cfm) prototype unit developed by Braxton Corporation and tested by GCA/Technology Division[2] incorporated an electromagnetically driven piston to produce sound intensities of approximately 165 decibels (3.0 W/cm^2) in a chamber 0.75 m (2.5 ft) in diameter and 4.3 m (14 ft) in length, through which the contaminated gas flows. Water is added to this chamber at its top (it stands with its axis vertical) through Sonicore nozzles said to deliver spray with droplets $\sim$ 20 μm. The sound frequency ($\sim$370 Hz) and the chamber length are tuned to produce a standing wave 4.5 wavelengths long. The sound moves the particulate material with respect to the spray and with respect to itself, causing sonic agglomeration of particulates. The agglomerated material can more easily be removed than the unagglomerated material, thus the Braxton device is a pretreatment for fine particulate emissions to allow the use of a control device, such as a cyclone, which is not an efficient collector of particles smaller than a few microns.

POTENTIAL APPLICATIONS

The Braxton sonic agglomerator was conceived as a means of allowing the use of cyclones or low energy scrubbers in the control of fine particulates, obviating the use of high energy scrubbers, fabric filters or electrostatic precipitators.

Particle Characteristics

Particle Size - The agglomerator is most useful for particles too small to be collected by cyclones, <5 μm, yet not so small that they do not impact upon other particles and drops available for agglomeration, meaning particles >0.5 μm.

Particle Phase - This should not be important, although the likelihood of agglomeration may be affected by certain surface properties.

Particle Resistivity - This should be immaterial.

Particle Abrasiveness and Corrosiveness - These will influence the choice of construction material.

Gas Characteristics

Gas Flow - Variations in flow velocities should not be important, as changes in residence time by a factor of two did not significantly change performance of the agglomerator in the tests.

Gas Temperature - It would not be expected to be a major factor, although the increased viscosity of high temperature gas would tend to inhibit agglomeration and cyclone collection somewhat.

THEORY OF OPERATION

The CCA report gives a more detailed explanation of the theory than presented here.[2]

The standing acoustical wave set up by the sound generator produces gas oscillation throughout the chamber. The smallest particles oscillate with the gas, the largest particles and the drops remain almost unaffected by the gas oscillation. This produces a relative velocity between the smallest particles and the larger particles and drops, and these small particles are captured by the larger constituents through the various mechanisms discussed in Section XVII on the general theory of obstacle collectors. Impaction, interception, and diffusion would all be expected to play roles. The larger particles and the drops grow at the expense of the smaller particle fraction, then the larger particles and drops can be collected within the agglomerator or by a control device (such as a cyclone) downstream from the agglomerator. Because these fine particles are hardest to collect, in general, the use of the agglomerator might require a less costly method of particle control downstream from it.

COLLECTION EFFICIENCY

In this subsection we present the results of measurements and analysis done by GCA/Technology Division as part of their evaluation of the Braxton sonic agglomerator.[2]

The sonic agglomerator is intended primarily as an exhaust preconditioner to be used in conjunction with another collecting device such as, in the present case, a cyclone. Because of the physical obstruction it presents to the gas stream, however, the agglomerator itself will also have a certain collection capacity irrespective of its preconditioning capabilities. A proper assessment of the effectiveness of the agglomerator thus requires an investigation of the collection efficiency of the whole system, as well as an investigation of the collection efficiencies of its individual components; namely, the agglomerator and the cyclone.

The method used to study the collection efficiency of the Braxton Sonic Agglomerator System is shown schematically in Figure 10. Identical sampling systems, consisting of appropriate sampling probes, Aerotec

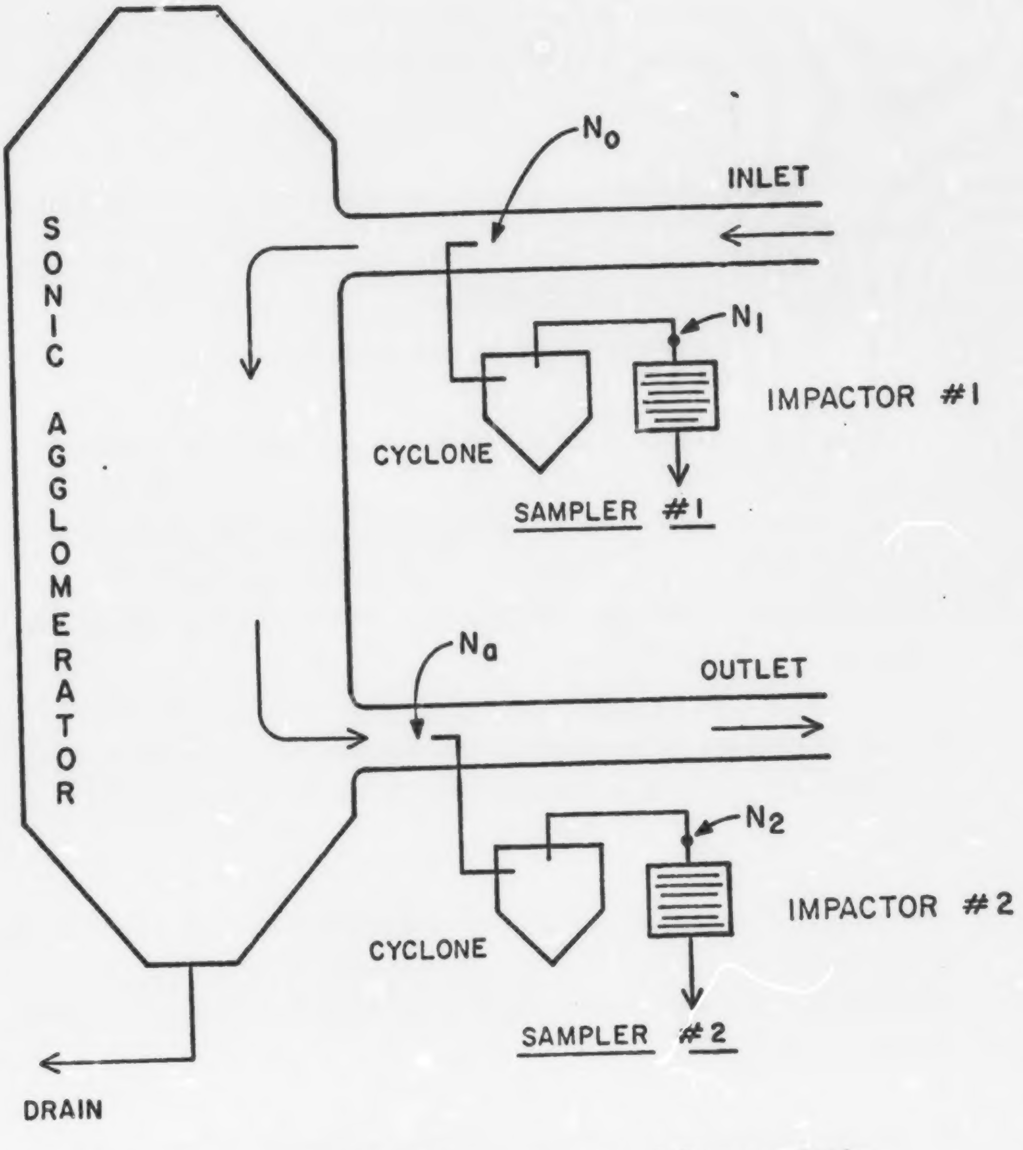

SONIC AGGLOMERATOR
N_0
INLET
N_1
IMPACTOR #1
CYCLONE
SAMPLER #1
N_a
OUTLET
N_2
IMPACTOR #2
CYCLONE
SAMPLER #2
DRAIN

Figure 10. Schematic diagram of test of Braxton Sonic agglomerator

model 1-1/2 cyclones, and Andersen six-stage cascade impactors, monitored the gas streams at the inlet and outlet of the sonic agglomerator. The larger-size dust fraction was separated by the cyclone, allowing the more interesting undersized portion to be analyzed with the cascade impactor. More details are available in the original report.

The different particle concentrations obtainable from the test configuration were:

- Total mass concentration
- Mass concentration of particles larger than cyclone cut-off size
- Mass concentration of particles smaller than cyclone cut-off size
- Size distribution of particles smaller than cyclone cut-off size

These were available upstream and downstream from the sonic agglomerator.

The inlet aerosol concentration for a given particle size is N_o. The concentration which reaches impactor No. 1 is N_1:

$$N_1 = (1 - E_c)\, N_o$$

where E_c is the cyclone collection efficiency at that particle size.

The cyclone collection efficiency as a function of particle size (Aerodynamic diameter) was taken from its manufacturer's specifications.

The concentration at the outlet of the agglomerator is N_a where

$$N_a = (1 - E_a)\, N_o$$

and E_a is the collection efficiency of the agglomerator, again at the particular particle size.

The concentration which reaches impactor No. 2 is N_2:

$$N_2 = (1 - E_c)\ N_a$$

Concentrations as functions of particle size (aerodynamic diameter) were obtained from the cascade impactor measurements. Thus, $N_2(d_p)$ would be the mass concentration as determined by each stage of the outlet cascade impactor, with d_p being a particle size which is characteristic of the material caught on each stage. The collection efficiency as a function of d_p for agglomerator plus cyclone is calculated from the ratio N_2/N_0, where N_0 is the stage-by-stage mass concentration as calculated from the results of sampling with the cascade impactor on the inlet. Because the impactors at the inlet and outlet of the agglomerator were the same, the collection efficiency of the agglomerator (for particle size d_p) is simply N_2/N_1, with N_2 and N_1 being the stage-by-stage mass concentrations from the impactors No. 2 and No. 1.

In the field study, the data were generated using a cyclone efficiency curve based upon a particle specific gravity of 2.5 and a cascade impactor cut-off size based on a particle specific gravity of 2.0. To facilitate comparisons, the data have here been converted to aerodynamic diameter size intervals. These data are summarized in Table 2.

Table 2 lists several collection efficiencies versus particle aerodynamic size intervals traceable to the cascade impactor sizing intervals. The measured values are the direct basis for collection efficiency of cyclone plus agglomerator. The manufacturer's data was interpolated to give the cyclone efficiencies shown, and the efficiency of the agglomerator only was calculated from the other two values (the penetration through both agglomerator and cyclone being the product of the penetrations through each). Figure 11 presents these in graphical form. From this information we can deduce that the agglomerator-cyclone combination had 50 percent efficiency at particle aerodynamic diameters around 2 μm; cyclone 50 percent efficiency occurred near 3 μm.

Table 2. FRACTIONAL COLLECTION EFFICIENCIES FOR THE BRAXTON SONIC AGGLOMERATOR SYSTEM, CYCLONE, AND AGGLOMERATOR/CYCLONE COMBINATION

Size interval aerodynamic diameter (in μm)	Agglomerator and cyclone	Agglomerator only	Cyclone only
< 0.5	59.40%	56.35%	7.0%
0.5-1.0	42.90	29.95	18.5
1.0-2.0	47.09	20.44	33.5
2.0-3.2	55.28	13.99	48
3.2-5.5	88.21	65.00	66.3
5.5-9.2	87.80	26.08	83.5
9.2-14.1	96.91	43.89	94.5

Some other results of these tests are worth noting. Tables 3 and 4 show the conditions of the tests and the collection efficiencies with respect to total mass and to the fine fraction escaping capture in the cyclone. Reduction in fine particles ($d_p \leq 3$ μm) ranged from 14 to 83 percent. The following correlation coefficients were found for the reduction in fine particles using sound, water, and steam:

sound - 0.68
water spray - 0.65
steam - 0.06

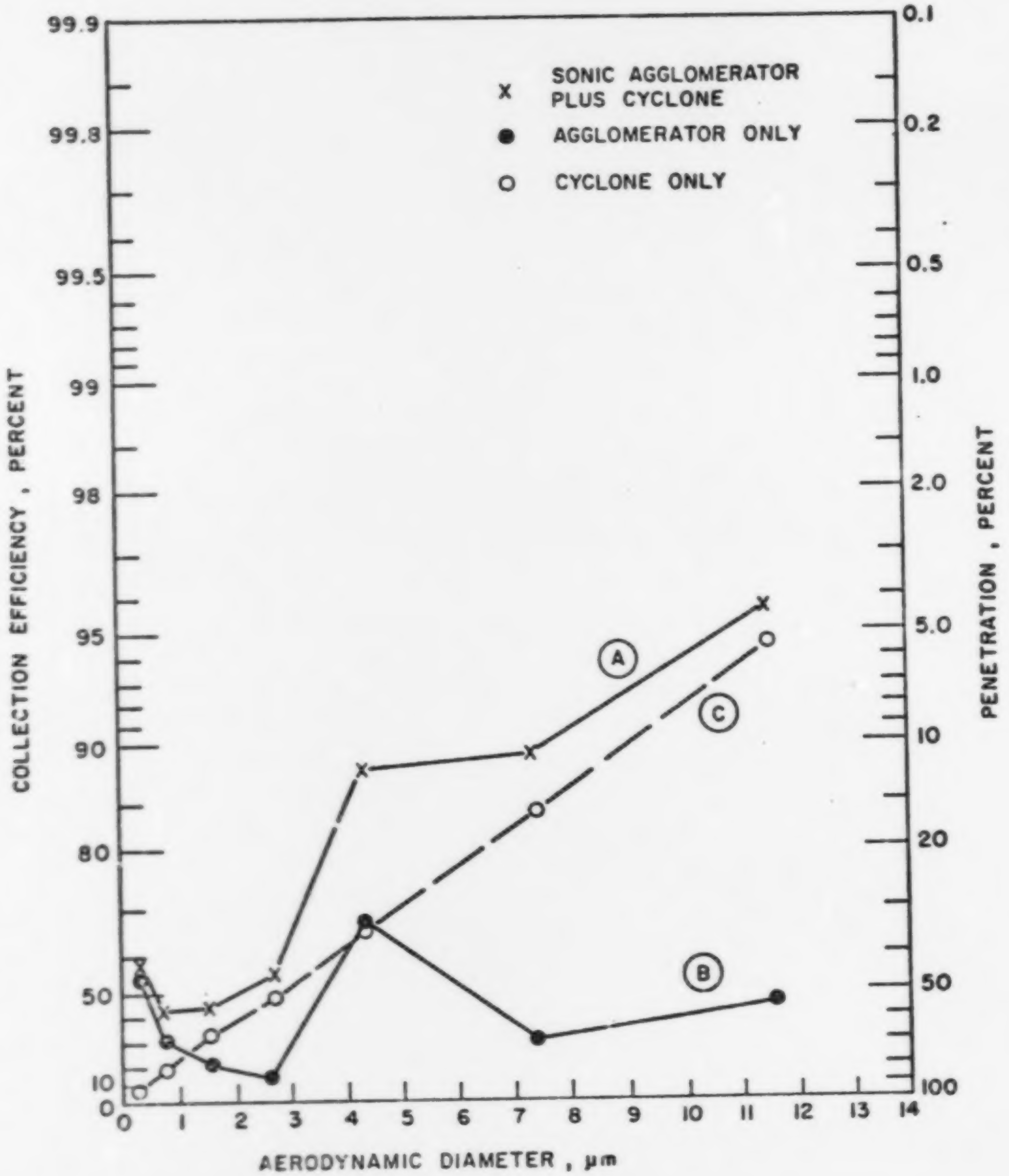


Figure 11. Collection efficiencies versus aerodynamic diameter for cyclone, agglomerator, and cyclone plus agglomerator

Table 3. SONIC AGGLOMERATOR SYSTEM OPERATING PARAMETERS[2]

Run no.	Date	Test dust	Volume flow m^3/s	Pressure drop across sonic chamber $n/m^2 \times 10^{-3}$	Fan power[a] kilowatts	Steam		Water		Sonic generator	
						Pressure $n/m^2 \times 10^{-3}$	Flow $m^3/s \times 10^5$	Pressure $n/m^2 \times 10^{-4}$	Flow $m^3/s \times 10^5$	Intensity db	Power kilowatts
1	10/17/73	cupola	2.22	2.96	12.40		0		0	0	
2	10/17/73	cupola	2.22	2.96	12.40		0	10.34	8.20	164	3.25
3	10/18/73	cupola	2.22	2.96	12.40		0	10.34	8.20	164	2.90
4	10/24/73	cupola	2.22	2.96	12.40		0	10.34	8.20	166	2.90
5	11/2/73	cupola	2.23	1.09	4.94		0	10.34	4.42	165	3.60
6	11/13/73	cupola	2.23	1.09	4.94		0	10.34	4.42	0	
7	11/13/73	cupola	2.23	1.09	4.94		0	10.34	4.42	165	3.00
8	11/19/73	cupola	2.47	1.09	5.48	3.45	2.27	6.90	4.42	164	3.20
9	11/19/73	cupola	2.48	1.09	5.50	3.45	2.27	6.90	4.42	0	
10	11/29/73	cupola	2.48	1.09	5.50	48.26	11.35	6.90	4.42	164	3.10
11	1/2/74	cupola	Dust feeder failure								
12	1/2/74	cupola	0.82	0.12	0.20	3.45	2.27		0	c	3.20
13	1/4/74	cupola	3.72	2.53	19.19		0		0	0	
14	1/4/74	cupola	3.72	2.53	19.19	3.45	2.27	6.90	4.42	161	3.00
15[b]	1/22/74	fly ash	2.48	1.09	5.50		0		0	0	
16	1/22/74	fly ash	0.82	0.12	0.20	20.68	7.72		0	162	3.30
17[b]	2/19/74	cupola	2.47	1.09	5.48		0		0	0	
18	2/19/74	fly ash	2.47	1.09	5.48	3.45	2.27	10.34	4.42	164	3.20
19	2/19/74	fly ash	2.47	1.09	5.48	3.45	2.27	10.34	4.42	165	3.50

[a] Fan power based on motor-fan combined efficiency of 55%.

[b] Runs 15 and 17 were to determine mass efficiency by size of sampling cyclone only.

[c] Microphone broken - sound intensity unknown.

Table 4. COMPARISON OF INLET AND OUTLET DUST LOADING, CYCLONE CATCH, CYCLONE UNDERSIZE DUST AND OVERALL SYSTEM COLLECTION OF ALL PARTICLE SIZES

Run no.	Inlet			Outlet			Reduction in mass of fine particles, percent $\frac{(A\ C)-(D\ F)}{A\ C} \times 100$	Reduction of total mass, percent $\frac{A-D}{A} \times 100$	System efficiency if followed by cyclone, percent $\frac{A-(D-D\ E)}{A} \times 100$
	A	B	C	D	E	F			
	Concentration g/m^3	Cyclone fraction	Filter fraction	Concentration g/m^3	Cyclone fraction	Filter fraction			
1	1.3309	.836	.164	0.7707	.657	.343	-20.9	42.1	80.1
2	1.5859	.809	.191	0.1965	.368	.632	59.4	87.7	92.3
3	1.8343	.906	.094	0.2629	.756	.244	62.8	85.7	96.5
4	2.2744	.869	.131	0.3121	.568	.432	54.9	86.3	94.1
5	1.1202	.887	.113	0.2126	.626	.374	37.0	81.0	92.9
6	1.1982	.794	.206	0.3806	.569	.431	33.6	68.2	86.3
7	1.6875	.850	.150	0.4639	.713	.287	47.2	72.5	92.1
8	1.2012	.902	.098	0.1648	.391	.609	14.6	86.3	91.6
9	0.8792	.875	.125	0.1499	.472	.528	28.1	83.0	91.0
10	1.5213	.886	.114	0.2352	.507	.493	33.0	84.5	92.4
12	0.9227	.698	.302	0.5824	.702	.298	37.8	36.9	81.2
13	2.5218	.931	.069	1.0376	.756	.244	-45.8	58.9	90.0
14	2.0105	.942	.058	0.1856	.723	.277	55.3	90.8	97.4
16	2.5690	.983	.017	0.2799	.899	.101	34.0	89.1	98.9
18	6.0677	.951	.049	0.3936	.879	.121	84.0	93.5	99.2
19	5.4163	.965	.035	0.4069	.922	.078	83.2	92.5	99.4

The first two were statistically significant. GCA also put this in the form of a multivariate regression formula:

$$R = -15.1 + 6.5\ W + 8.3\ S$$

where

R = percentage reduction in fine particle mass
W = spray water flow, $10^{-5} m^3/s$
S = sonic generator power, kW

The -15.1 in the equation reflects the interesting observation that although the sonic agglomerator collected, by itself, from 42 to 59 percent of the particulate matter entering it (fly ash, cupola dust) even without steam or sound or water, the agglomerator increases the fraction of fine particles under these conditions, presumably due to shear de-agglomeration.

POWER CONSUMPTION

Most of the field tests on the prototype model were conducted with gas flows on the order of 2.4 m^3/s (5000 cfm). Practical applications will require higher gas flows; the power requirements for this system have been calculated per 1000 cfm (0.47 m^3/s).

Power consumption is based on the relationship:

$$P = Q\ \Delta P$$

in which P is the power; Q the gas flow rate; and Δp the pressure drop across the system. Since the flow rate is assumed (0.47 m^3/s), the only variable needed to calculate the power consumption is the pressure drop, ΔP, which can be estimated from cyclone design theory.

The following calculations of the pressure drop for the scaled version of the cyclone system to be used with the Braxton Sonic Agglomerator are based on a recent review of cyclone design theory by Leith and Mehta.[3] In cyclone theory, the pressure drop is often expressed in terms of inlet velocity heads **ΔH:**

$$\Delta H = K \frac{a\ b}{D_e^{\ 2}}$$

in which K is a constant (K = 16 for a standard tangential inlet); a is the gas inlet height; b is the gas inlet width; and D_e is the cyclone exit duct diameter. If one of the dimensions of the cyclone is known (e.g., b, the width of the inlet duct), the others can be obtained from standard dimension ratios. For a Stairmand type cyclone, $a/D = 0.5$, $b/D = 0.2$ and $D_e/D = 0.5$, where a, b, and D_e are as defined above and D is the diameter of the inlet duct.

The gas inlet width, b, can be calculated from:

$$d_{pc} = 3\left[\frac{\mu\ b}{2\ \pi\rho_g\ v\ N}\right]^{1/2}$$

where d_{pc} is the particle aerodynamic cut-off diameter, the aerodynamic diameter (Appendix) for which the cyclone penetration is 50 percent; μ is the gas viscosity (1.8×10^{-4} poise); ρ_g is the particle density; v is the gas velocity and N is a constant (usually 5). The gas velocity, v, can be calculated from the relationship:

$$v = Q/A$$

in which Q is the gas flow rate (m^3/s) and A is the area of the inlet duct (note - from the standard design dimension ratios, $A = ab = 2.5\ b^2$). Using the Aerotec cyclone manufacturer's value for the cut-off diameter, $d_{pc} = 2.76\ \mu m$, the inlet width, b, can be calculated from the equations. Knowing b as well as standard design dimension ratios permits ΔH to be calculated. The pressure drop in terms of inlet velocity heads, ΔH, can then be converted to static pressure ΔP, required for the power calculation, by the following expression:

$$\Delta p = \frac{v^2 \rho_g \Delta H}{2 g \rho_L}$$

in which v is the gas velocity; ρ_g, the gas density (1.2×10^{-3} g/cm^3); g, the acceleration of gravity (980 cm/s^2); ρ_L, the reference liquid density (1 g/cm^3).

Using the last four equations, the pressure drop, Δp, required to pass, say, 4.7 m^3/s (10,000 cfm) of gas through a single Stairmand cyclone with a cut-off diameter of 2.76 μm is 7.5×10^5 N/m^2 (7.5 atm), which is impractically high. However, multiple cyclones, for example a group of 10, each capable of handling 0.47 m^3 (1000 cfm), can be arranged to provide the equivalent throughput with a much lower pressure drop. For this arrangement, these equations predict a pressure drop of 7.5×10^3 N/m^2 (75 cm WC), which would be 4.75 hp/1000 acfm or 7.5 kW/(m^3/s), still quite high.

A low-power venturi scrubber with a particle cut diameter of 3 μm would give roughly equivalent collection efficiencies if used rather than the cyclone; its pressure drop would be 300 N/m^2 (3 cm WC) approximately,[4] much less than the cyclone.

In addition to the cyclone power consumption, the power requirements of the sonic generator as well as the power needed to move gas through the agglomerator should be considered. In the prototype tests,[2] for gas flows of 2.2 m^3/s the sonic generator operated typically at 3 kW. Using a simple multiplier scaling, the power necessary for 0.47 m^3/s should be on the order of 0.6 kW or 0.8 hp/1000 cfm.

Operating the agglomerator itself requires a pressure drop of approximately 750 N/m^2 (7.5 cm WC),[2] which at the flow rate of interest (0.47 m^3/s), would require, 0.35 kW or 0.47 hp/1000 cfm.

The overall power requirements then for whole system: the high efficiency cyclone, the sonic generator, and the agglomerator should be about 4.5 kW at 0.47 m^3/s or 6.0 hp/1000 cfm, equivalent to 96 cm WC pressure drop; substitution of the low-energy scrubber for the cyclone lowers this consumption to about 2.4 kW/(m^3/s) (1.5 hp/1000 cfm), equivalent to a pressure drop of 24 cm WC.

WASTE DISPOSAL

The material caught by the agglomerator itself will flow out of its liquid exhaust stream as a sludge, which would be handled as scrubber sludges are. The material collected by the control device used in conjunction with the agglomerator would be handled as it normally is.

SECTION VI

CENTRIFIELD SCRUBBER

DESCRIPTION

This material is taken from the manufacturer's literature as cited by Southern Research Institute in its evaluation.[5] "Modern, high-efficiency wet scrubbers for the removal of entrained particulates from industrial exhaust gases depend, almost without exception, on spray contact for particle interception. The atomization and acceleration of the scrubbing liquid into contacting zone can be performed by a wide variety of mechanical arrangements. A new high-performance contactor, the centripetal vortex contactor, is now available.

"The centripetal vortex principle is illustrated in Figure 12. For any point on radius r_c and tangential gas velocity v_t, a particle may exist whose terminal velocity toward the vortex periphery exactly equals radial gas velocity v_r. If the particles consist of liquid droplets, and the peripheral inlet vanes are of the proper configuration, the vortex selectively develops a specific droplet diameter distribution within the rotating field, as determined by r_c, v_i, and ϕ. The average droplet diameter created by a field of this type is substantially smaller than that by a conventional spray contactor at the same energy level. Droplet diameter is one of the basic parameters of spray contactor efficiency.

"Gas scrubber performance is most conveniently described by the relationship: $N_t = aP^{\gamma}$, where $N_t = \log_e \left[1/(1\text{-collection efficiency})\right]$ and P = energy input per unit of gas treated. For a given dispersoid, an

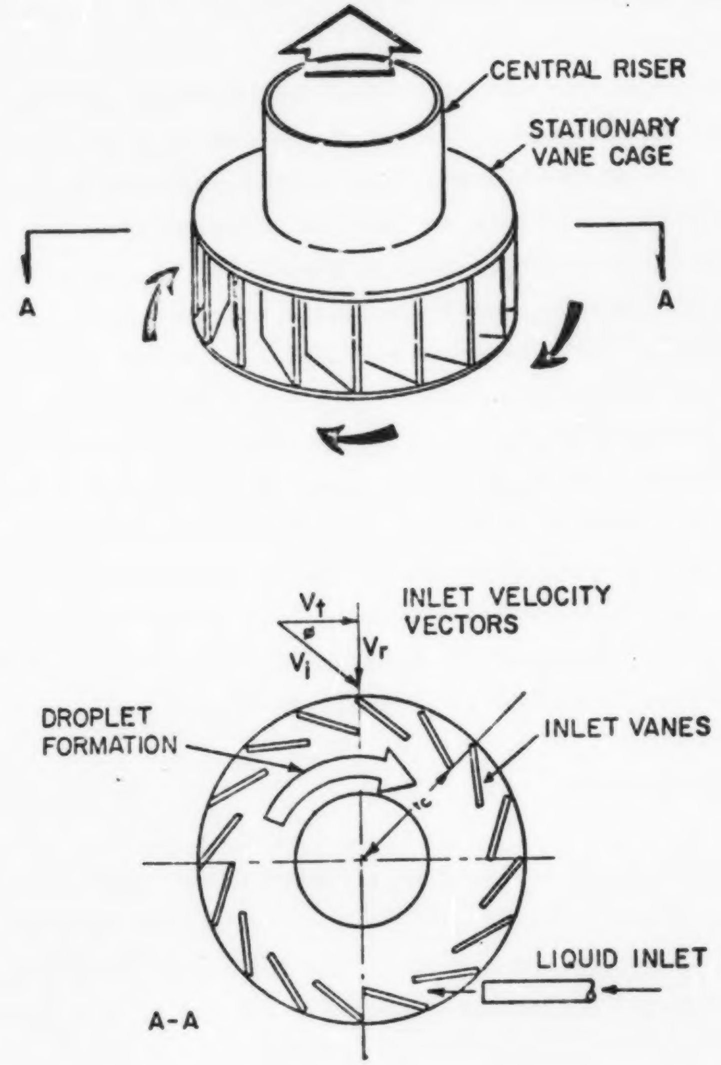

CENTRAL RISER
STATIONARY VANE CAGE
A
A
Vt
INLET VELOCITY VECTORS
ø
Vr
Vi
DROPLET FORMATION
INLET VANES
rc
LIQUID INLET
A-A

Figure 12. Centripetal vortex balances gas velocity against centrifugal force

improvement in gas scrubber design results in an increase in a. The centripetal vortex principle should theoretically increase a by approximately 20 percent over a conventional contactor. Laboratory and field tests show an increase of 15 to 25 percent. This is a significant improvement in scrubber performance in relation to energy input.

"The droplet formation within a spray contactor is inherently in co-current flow in respect to the gas stream, which limits its gas absorption efficiency to a maximum of one theoretical plate per stage. Nevertheless, spray contactors, in single or multiple stage arrangements, are often the only feasible mass transfer device, especially in applications where insoluble particulate is present, or where the product of the absorption process tends to foul conventional packing and sieve plates. Mass transfer efficiency in a spray contactor is, as would be expected, a function of L/G ratio and specific droplet surface area. Since specific surface area varies inversely with droplet diameter, it is reasonable to expect that the centripetal vortex, with its unusually small equilibrium droplet diameter, would exhibit superior mass transfer capabilities. Laboratory and field data have confirmed this expectation. Under circumstances where an active reagent is involved, mass transfer efficiencies approaching equilibrium have been recorded at nominal pressure drops."

POTENTIAL APPLICATIONS

The Centrifield scrubber would be expected to be applied to situations in which other scrubbers would also be candidates such as steel mills, foundries, refineries, paper mills and other industries with fine, sticky or liquid emissions. The device tested for EPA was in use on an asphalt plant.

Particle Characteristics

Particle size - The scrubber was found to give 99 percent or better collection efficiency for particles with aerodynamic diameters larger than

3 to 4 μm, but less than 80 percent for particles with aerodynamic diameters from 0.1 to 1 μm.

Particle Phase - Liquids or solids should be acceptable.

Resistivity - Collection should be independent of resistivity.

Abrasiveness - Special materials may be necessary in certain cases.

Corrosiveness - Similar considerations apply as for abrasiveness.

Gas Characteristics

Gas Flow Rate - For the same geometry, increasing the volume flow rate will linearly increase the inlet gas velocity and increase by the square the centrifugal force on the droplets; the equilibrium droplet size would be expected to change as the inverse square root of the volume flow rate, not a strong dependence. The relative radial velocity of the gas and droplets would increase with the gas volume flow, enhancing impaction. The rate of droplet evaporation will increase due to the ventilation factor. The foregoing sketches some of the complexities involved in predicting the effect of flow rate. Presumably, the scrubber is designed to be maximally efficient at a given flow rate, with somewhat degraded performance when this optimum is not met.

Gas Temperature - Almost all particle collection mechanisms, except diffusion (significant only for particles $\lesssim 0.1$ μm diameter), are inhibited by higher gas temperatures, and the problem is aggravated in scrubbers by the change in volume flow rate and the increased droplet evaporation, both generally to the detriment of collection efficiency.

THEORY OF OPERATION

The droplets formed in the Centrifield Scrubber collect particles by mechanisms such as impaction and diffusion, as outlined more fully in Section XVII on general theory of collectors. The flow geometry of the scrubber is said to be such that the droplets are formed so as to be smaller than those of conventional scrubbers, for the same power input. Inertial impaction and diffusion are both enhanced by decreases in droplet size, other things being equal. The device also is said to maintain a high concentration of droplets in the scrubbing section by balancing the velocity which would occur due to "centrifugal force" against the radial component of the air flow velocity. This would also be expected to increase scrubbing efficiency. Offsetting some of these advantages, however, is the fact that the droplets which remained in the scrubbing section would reach the same tangential velocity as the gas/particle mixture and the collection due to relative motion (impaction and interception) would be then due only to relative radial velocities. These potentially important details aside, the device acts basically in a manner similar to that of other spray scrubbers in collecting particulates and, to a degree, gases.

COLLECTION EFFICIENCY

Southern Research Institute (SoRI) tested the Centrifield Scrubber in operation on a four-ton asphalt plant equipped with a dryer having a capacity of 250 ton/hr and burning No. 2 fuel oil. The plant was operated intermittently. Total mass efficiency measurements were made by taking simultaneous representative samples upstream and downstream by standard methods (EPA "Method 5") giving values of 99.50 and 99.73 percent collection efficiency on the particulate material, which had a mass mean diameter around 100 μm. Efficiencies as functions of particle size were obtained by using the following instruments upstream and downstream:

- impactors
- optical counter
- diffusion battery/condensation nuclei counter
- electrical mobility analyzer

The impactors were used at inlet and outlet test points (Figure 13) during the same run; the other equipment was used either on the inlet or the outlet during the run. Rather rapid variations in concentration due to variations in the process made accurate assessment of true mean particle concentrations difficult, leading SoRI to estimate the final precision to be about a factor of two.

Figure 14 is taken from the SoRI report and shows the collection efficiency as a function of particle size for the Centrifield scrubber they tested. The particle sizes determined by optical measurements were converted to geometric sizes assuming the light scattering to be that due to polystyrene latex of the size indicated; the geometric size was estimated from impactor measurements by assuming spherical particles of density 2.5 g/cm^3. Minimum collection efficiency occurs for particles a few tenths micron in diameter, as expected.

Figure 15 is another figure taken from the SoRI report on the Centrifield scrubber. Here efficiency is graphed against aerodynamic diameter as determined from measurements using cascade impactors at the inlet and outlet of the scrubber. The curve of efficiency versus aerodynamic diameter is directly comparable to other such curves obtained for novel control devices in other evaluations in this series. The aerodynamic diameter at which the collection efficiency is 50 percent appears to be between 0.6 and 0.7 μm.

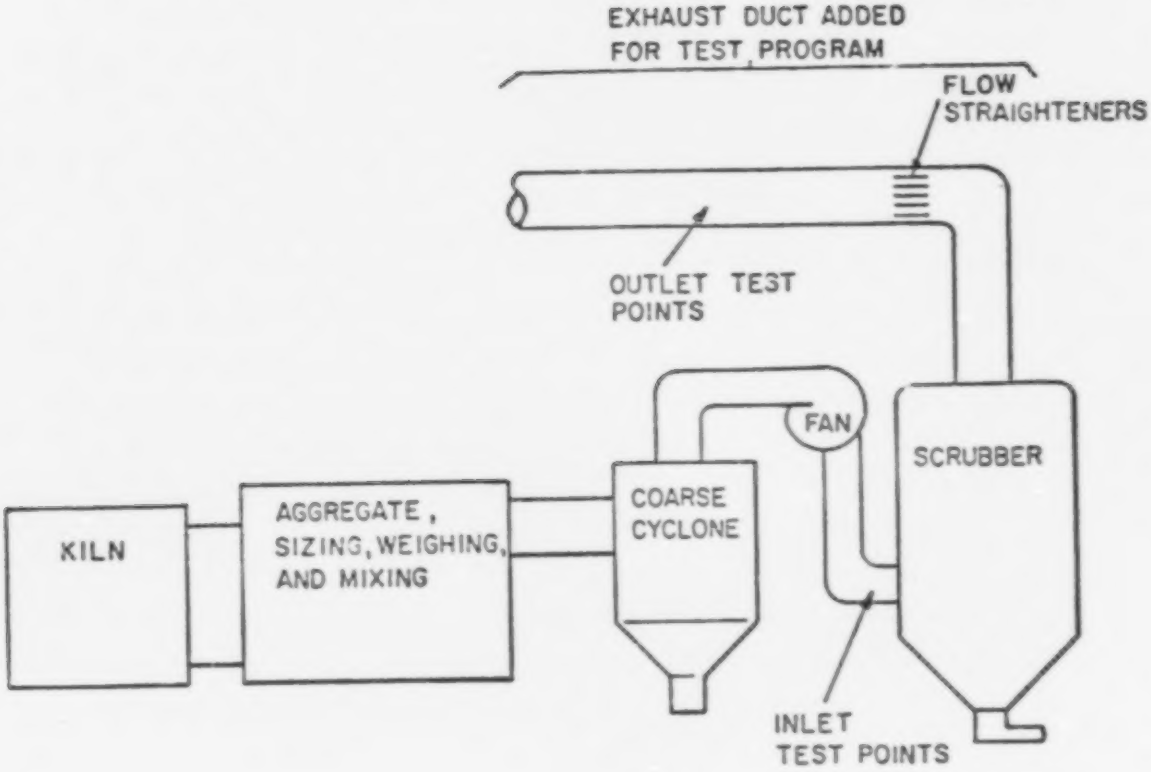

EXHAUST DUCT ADDED FOR TEST PROGRAM
FLOW STRAIGHTENERS
OUTLET TEST POINTS
FAN
SCRUBBER
COARSE CYCLONE
KILN
AGGREGATE, SIZING, WEIGHING, AND MIXING
INLET TEST POINTS

Figure 13. Schematic diagram of the asphalt plant and scrubber layout and the locations of the sampling points used in the tests[5]

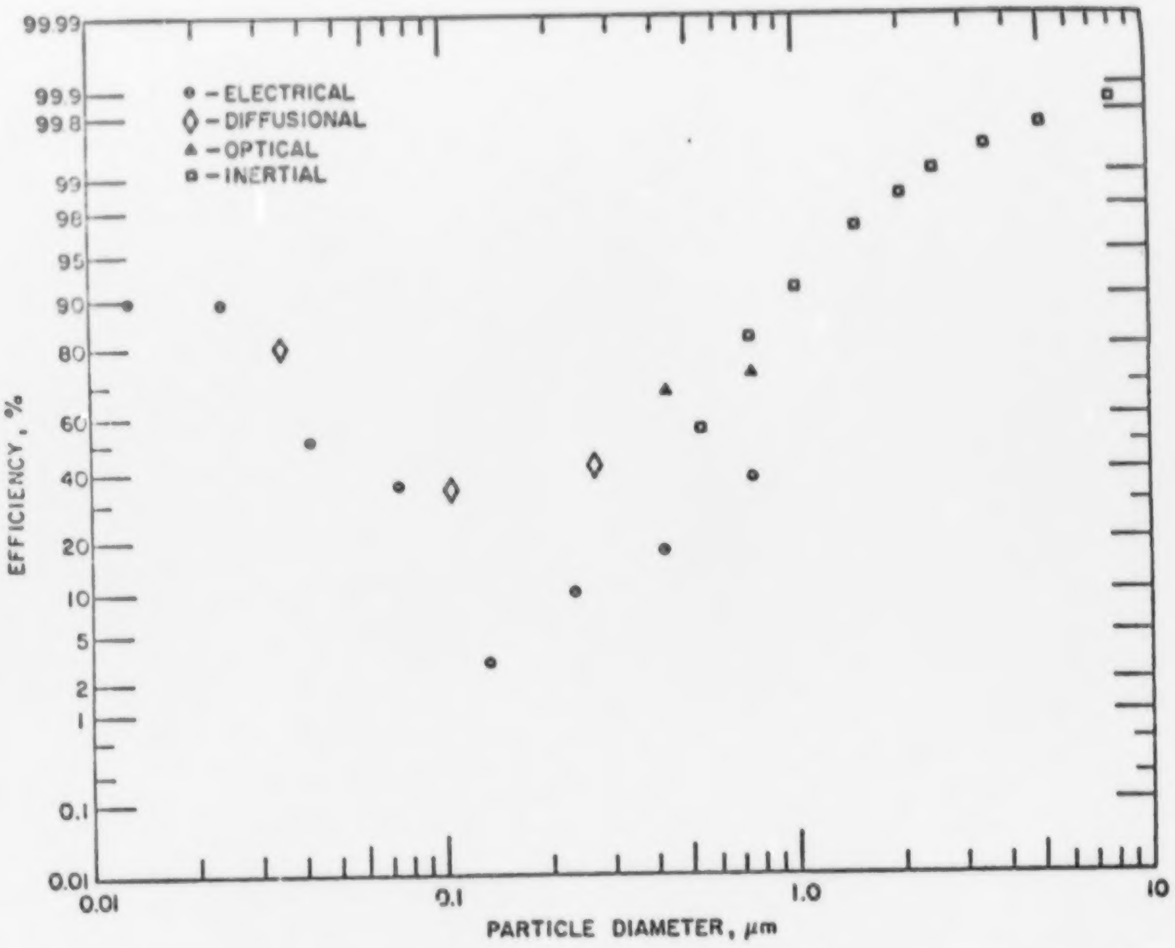


Figure 14. Fractional efficiencies as determined by the four methods used in the test program. The particle sizes shown for the impactor data are Stokes Diameters based on a particle density of 2.5 grams/cm^3.[5]

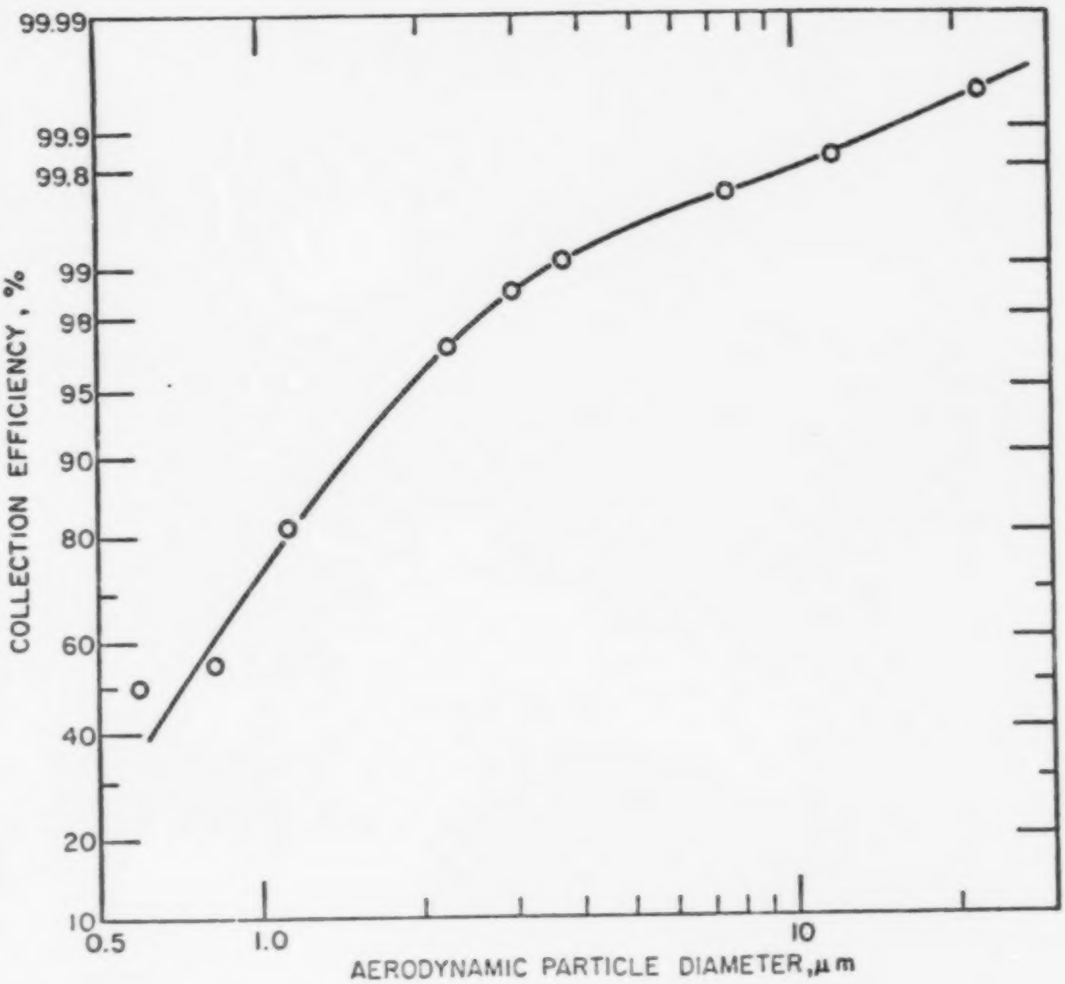


Figure 15. Fractional efficiencies of the Entoleter Centrifield Scrubber as determined from cascade impactor data [5]

POWER CONSUMPTION

The Centrifield scrubber tested by SoRI has a pressure drop of 17 cm WC or 6.7 inches WC. This is the equivalent of 1.66 $kW/m^3/s$ or 1.06 hp/ 1000 acfm.

Water consumption was measured to be about 0.5×10^{-3} m^3 water per m^3 air or 4 $gal/1000\ ft^3$.

WASTE DISPOSAL

As with any scrubber, the waste will be in the form of waterborne solids, which will either be sent to a receiving body or treated. More detail is given on the section on waste treatment, within Section XIV.

SECTION VII

CLEANABLE HIGH EFFICIENCY AIR FILTER (CHEAF)

DESCRIPTION

The CHEAF operates by drawing gas and particulate material at high velocities through a porous polyurethane foam structure which is wetted by a water spray. The system has recently been purchased from the Johns-Manville Corporation by Andersen 2000, Inc. of Atlanta, Georgia.

POTENTIAL APPLICATIONS

Based on our limited information, the following considerations would apply to applications of the CHEAF system.

Particle Characteristics

Particle Size - Collection efficiency in the tests performed for the Industrial Environmental Research Laboratories - Research Triangle Park, EPA, showed essentially no effect of particle size on efficiency. It is possible that preferential collection efficiency with respect to particles larger than a micron were offset to a degree by penetration of agglomerated materials of nearly the same size.

Particle Phase - Presumably the CHEAF would find insoluble viscous droplets to be more difficult to clean than other aerosol types.

Resistivity - This should have no influence on the CHEAF's performance.

Abrasiveness - By locating the air-mover downstream from the control device, its abrasion can be minimized.

Corrosiveness - This is potentially a problem in any system, and can usually be handled through suitable choice of materials.

Gas Characteristics

Gas Volume Rate of Flow - The collection efficiency would be expected to be somewhat dependent upon flow rate.

Gas Temperature - The CHEAF can be operated with a quenching system to reduce the temperature to within its operational range.

THEORY OF OPERATION

The collection mechanisms would be those described in Section XVII on general theory of obstacle collectors. The porosity of the foam is 90 percent and the characteristic collector dimension of the 65 pore per inch foam (26 pore per cm) is on the order of 10^2 μm. The ratio of the water spray rate to the air volume flow rate is about 10^{-4} (about 1 gal/1000 cfm). As part of an expanded evaluation of the CHEAF, GCA/Technology Division is testing it on laboratory-generated iron oxide aerosols and formulating a model to describe its collection mechanisms.

COLLECTION EFFICIENCY

The evaluation was done by Air Pollution Technology, Inc. (APT).[6] Cascade impactors were used upstream and downstream from the CHEAF while it was in operation on a 53.2 m^3/s (25,000 acfm) diatomaceous earth calcining and drying process. The CHEAF was downstream from a cyclonic precleaner with water sprays. Saturated gas (at 63°C) went from the cyclonic precleaner through flow straighteners, past the inlet sample port to the CHEAF, then to a blower and to the main stack, where the outlet ports were. This is shown schematically in Figure 16. APT used heated University of Washington Mark III impactors for the size distribution work and attempted to use diffusion batteries with condensation nuclei counting as well, without success. The total mass concentrations were measured with the standard equipment and procedures usually referred to as EPA Method 5.

Even with a device used to remove the spray droplets at the inlet of the impactors, there was quite a bit of difficulty due to moisture. Several successful tests were achieved, however, and Figure 17 is derived from the APT results, showing collection efficiency as a function of particle aerodynamic diameter. As APT noted, the efficiency is almost independent of particle size in the range measured.

Because the diatomaceous material is hygroscopic, there may have been considerable growth in particle size due to moisture addition. It is typical of such growth that the final particle sizes of the particles are much more nearly the same than were the dry particles. The particles were dried before sizing, masking any growth. This might be the explanation for the nearly uniform collection efficiency versus particle size. This is to be studied further in the tests underway by GCA.

Figure 18, from the APT report, shows inlet and outlet size distributions, in cumulative form - the percent smaller than a given aerodynamic versus the aerodynamic diameter. The distributions are nearly identical, with mass median aerodynamic diameters of 0.8 μm and geometric standard deviations of 3.8. The total mass efficiencies on this aerosol, according to the Method 5 sampling results, were 95.6 percent and 94.7 percent.

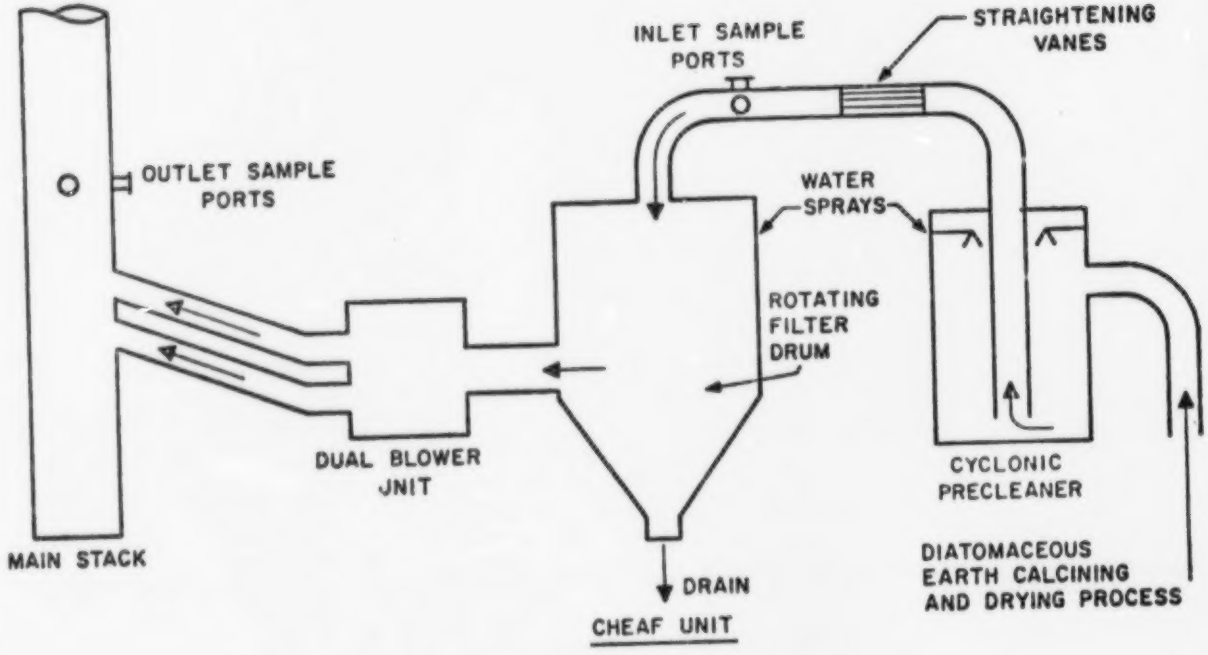

INLET SAMPLE PORTS
STRAIGHTENING VANES
OUTLET SAMPLE PORTS
WATER SPRAYS
ROTATING FILTER DRUM
DUAL BLOWER JNIT
MAIN STACK
DRAIN
CHEAF UNIT
CYCLONIC PRECLEANER
DIATOMACEOUS EARTH CALCINING AND DRYING PROCESS

Figure 16. Diagram of CHEAF installation[6]

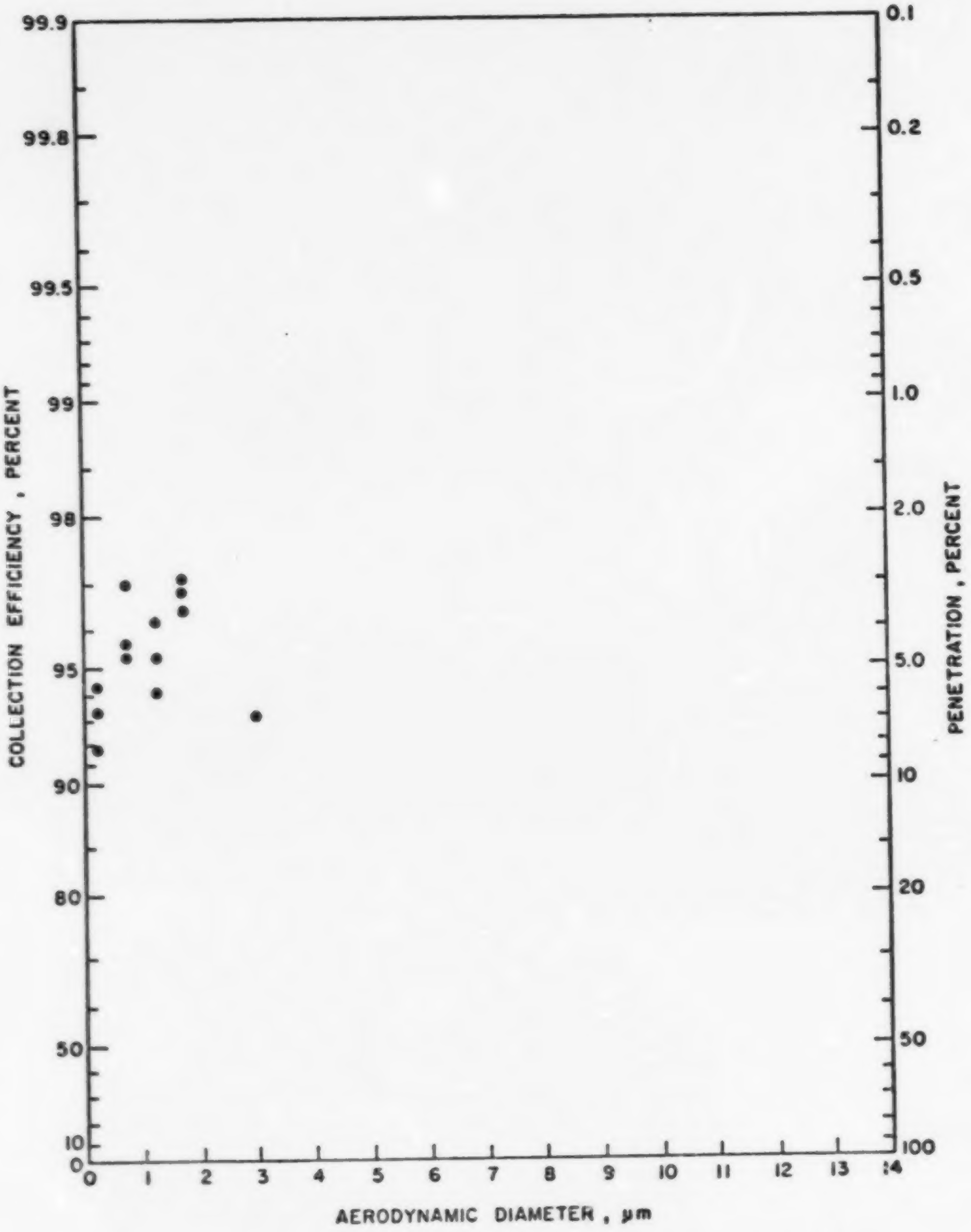


Figure 17. Collection efficiency versus aerodynamic diameter, CHEAF

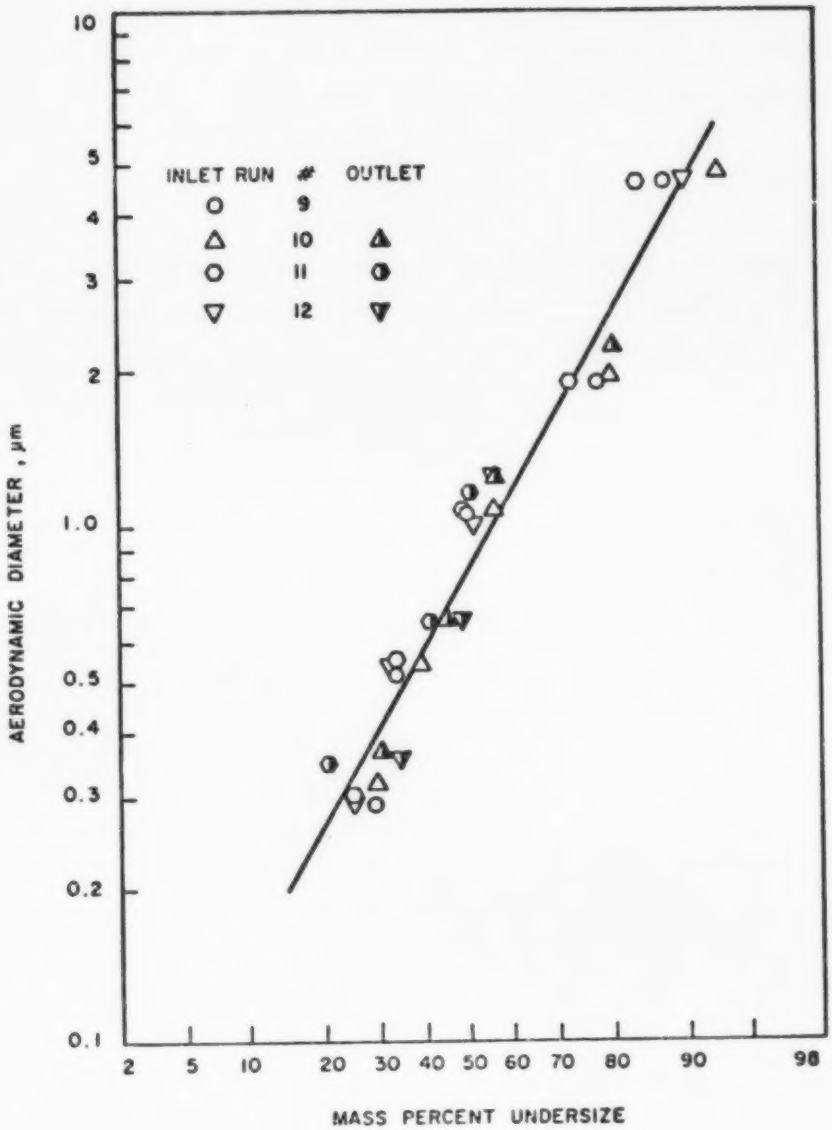


Figure 18. Inlet and outlet cumulative aerodynamic diameter distributions,[6] CHEAF tests

POWER CONSUMPTION

Pressure drop across the CHEAF system was reported to be about 53 cm WC (or 21 inches H_2O). This corresponds to 3.3 hp/1000 acfm or 5.2 kW/(m^3/s). This is the hydraulic power, the actual electrical power consumption would be obtained by dividing the hydraulic power by the efficiency factor for fan and motor combinations, usually about 0.6.

WASTE DISPOSAL

We have very little information regarding the wastes produced by the CHEAF system, but it is likely that they would be similar to the wastes created by scrubbers and would be handled similarly.

SECTION VIII

DYNACTOR SCRUBBER

MANUFACTURER'S DESCRIPTION[7]

The Dynactor uses a proprietary nozzle design to produce a water spray which serves as an air mover and as a scrubber, thus cleaning and propelling the gas simultaneously. A description of the Dynactor, written by its manufacturer (RP Industries, Hudson, Massachusetts), follows: "The continuous gas/liquid contactor, the Dynactor, is a proprietary development of RP Industries, Inc. Figure [19] is a cross section of a single stage Dynactor diffusion contactor. Liquid entering the system under a pressure of 140 to 200 pounds per square inch (typical) is atomized into thin films and droplets of average thickness or diameter less than 1/64 inch. This liquid discharge diffuses or expands into the reaction chamber causing air or gas to be aspirated by being trapped within the moving shower of films and particles. The resulting mixed fluid then continues to travel down the reaction column with intimate contact maintained between gas and liquid. This causes physical and chemical equilibria to occur by the time the mixed fluid exits from the reaction column into the separation reservoir. The Dynactor can be viewed as a macroscopic diffusion pump which makes use of diffusion principles in order to aspirate large volumes of air per volume of motive liquid. By utilizing diffusion rather than Bernoulli principles, the Dynactor aspirates up to 4,800 standard volumes of gas per volume of motive liquid. In comparison, venturi eductors will aspirate not more than 100 volumes of gas per volume of motive liquid.

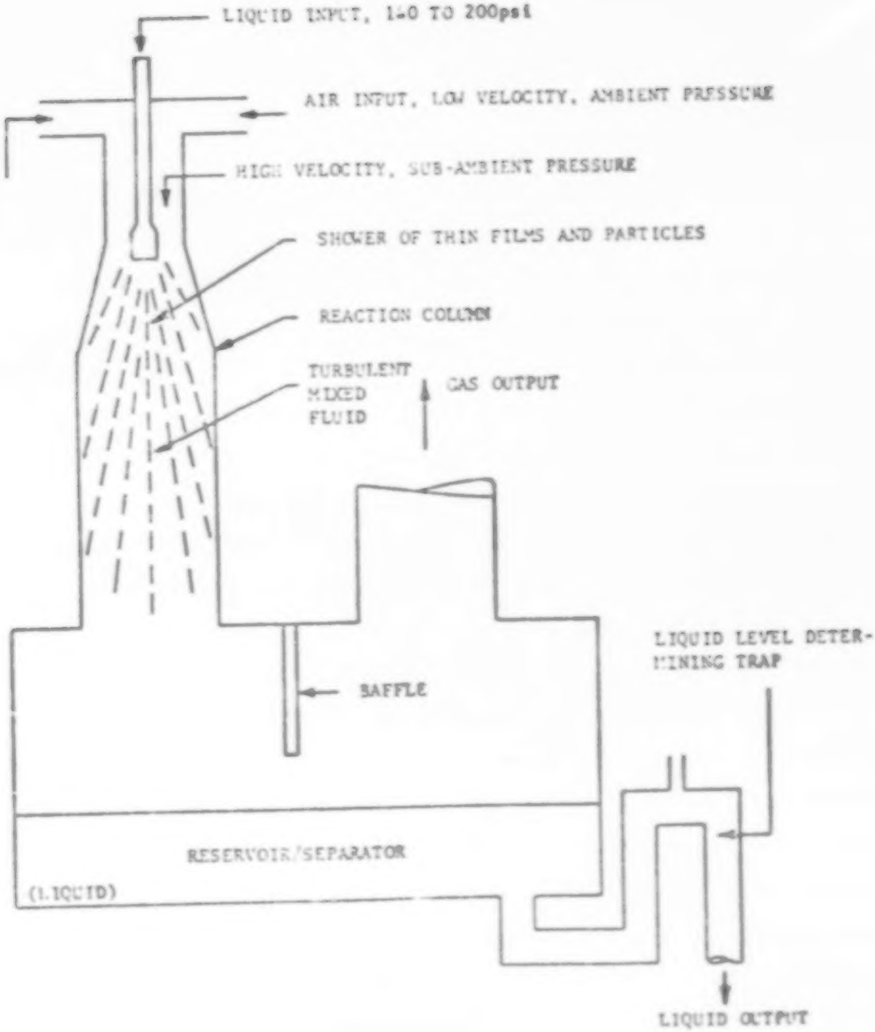

LIQUID INPUT, 140 TO 200psi
AIR INPUT, LOW VELOCITY, AMBIENT PRESSURE
HIGH VELOCITY, SUB-AMBIENT PRESSURE
SHOWER OF THIN FILMS AND PARTICLES
REACTION COLUMN
TURBULENT MIXED FLUID
GAS OUTPUT
BAFFLE
LIQUID LEVEL DETERMINING TRAP
RESERVOIR/SEPARATOR
(LIQUID)
LIQUID OUTPUT

Figure 19. Single-stage Dynactor diffusion system cross sectional view

"Because there are no venturi or other constrictions in the Dynactor, energy requirements are considerably lower than for conventional jet or venturi eductor systems. If the gas carries small solid particles along with it, such as activated carbon or powdered neutralizing and precipitating agents, such particles are wetted and captured by the liquid throughout the entire length of the reaction chamber. By contrast, venturi wet scrubbers make effective contact between gas and liquid only in the constricted throat region. Contact time, therefore, in the Dynactor is about 20 times longer than in venturi devices.

"Just as in oil and mercury diffusion vacuum pumps, it is also possible to construct Dynactors having multistage gas inputs." Figure 20 is a drawing of the two-stage Dynactor diffuser system employed in these studies. "The internal configuration was constructed to maximize gas/liquid turbulence and contact throughout the length of the 6-foot long, 12-inch diameter reaction column."

The unit tested by GCA/Technology Division was one of the smaller units of its type, a two-stage device with a nominal rating of 0.47 m^3/s (1000 cfm), Model DY 12 F2. Water was recirculated from the reservoir through pumps (one for each stage) to nozzles and was changed only after each test.

POTENTIAL APPLICATIONS

The Dynactor scrubber would be a candidate for application in those areas where scrubber technology has been shown useful, such as metallurgical operations, refineries, paper mills and industries which have fine, sticky or liquid emissions. Dynactors are used in textile processing to collect chemicals and plasticizers, in food processing to remove water soluble odors, in the plastic industry to collect chemicals and plasticizers, to condense hydrocarbons and remove polymer odors, to purify kiln outputs after cyclone preseparation, and to hood cupolas in foundries.

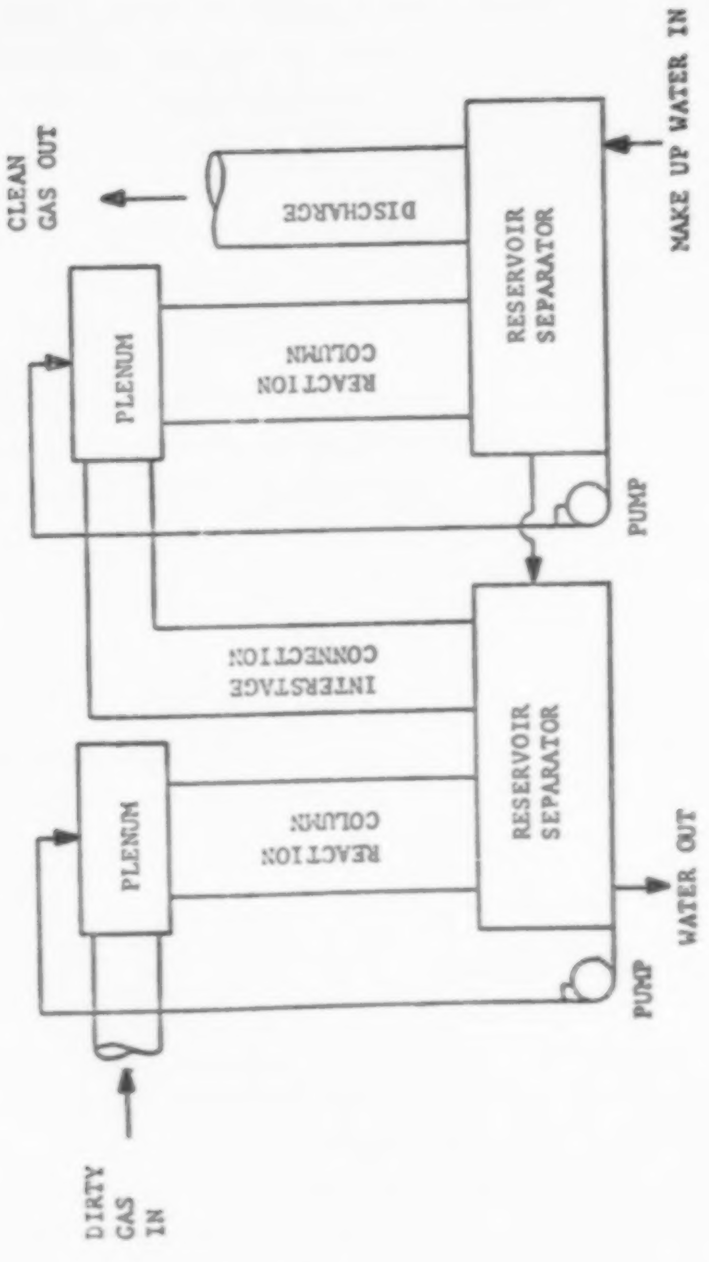

DIRTY GAS IN
PLENUM
REACTION COLUMN
RESERVOIR SEPARATOR
PUMP
WATER OUT
INTERSTAGE CONNECTION
PLENUM
REACTION COLUMN
RESERVOIR SEPARATOR
PUMP
CLEAN GAS OUT
DISCHARGE
MAKE UP WATER IN

Figure 20. Two-stage Dynactor

Applicability is discussed in more general terms next, with respect to particle types, gas characteristics, etc.

Particle Characteristics

Particle Size - The Dynactor was found to give efficiencies greater than 99 percent for particles larger than 4 μm aerodynamic diameter, but substantially less than 90 percent for those smaller than 1 μm.

Particle Phase - Solids were used in the tests for evaluation (fly ash and iron oxide), but it is expected that liquids (droplets) would be collected equally well.

Resistivity - Resistivity does not affect collection efficiency.

Abrasiveness - Abrasive aerosols may have a detrimental effect on water pumps and nozzles if they appear as suspended solids in recirculated water. The test series using abrasive aerosols (fly ash and iron oxide) did not noticeably effect pumps or nozzle after a total operating time of about 40 hours.

Corrosiveness - RP Industries constructs Dynactors from stainless steel, polypropylene, PVC, and fiberglass reinforced epoxy and polyester. Other construction materials are possible for difficult materials handling problems.

Gas Characteristics

Volume Rate of Flow - The largest Dynactor now available will move 24 m^3/s (50,000 cfm). Dynactors may be connected in parallel. RP Industries plans to develop a 470 m^3/s (10^6 cfm) unit.

Temperature - The Dynactor was tested at 93°C (200°F) with an insignificant decrease in collection efficiency. Hotter gases, fed directly into the Dynactor, may be more difficult to scrub. In one application, 830°C (1500°F) effluent gas is prechilled with water spray before flowing to the Dynactor.

Pressure - For proper Dynactor operation, the inlet gas should not be in vacuum in excess of 125 N/m^2 (1/2 " H_2O). This would not be troublesome for stack gas which is pressurized compared to atmosphere, but may present difficulties for some applications.

For some Dynactor installations, existing ducting may have to be shortened and/or widened to reduce flow resistance.

THEORY OF OPERATION

Particle Collection

As discussed in Section XVII on general theory of collection devices, this scrubber works primarily due to the motion of the collecting droplets with respect to the particle-laden gas stream. Details of this process in the Dynactor are proprietary or unknown. The two most significant collection mechanisms are expected to be impaction, which improves with increasing particle size, and diffusion, which improves with decreasing particle size. The interaction of these two mechanisms is expected to give a collection minimum $\sim 10^{-1}$ μm, as observed. Other mechanisms expected to contribute to collection: sedimentation, interception, agglomeration, condensation.

Air Induction

The spray from the Dynactor nozzles entrains air and produces air motion, helping to overcome resistance to air flow in the Dynactor and the ductwork to which it is connected. The nozzle hydraulic power is the product of its flow rate and pressure:

$$P_n = Q_\ell \Delta p_n ,$$

where

P_n = nozzle hydraulic power
Q_ℓ = water flow rate
Δp_n = nozzle pressure

At most, all this power would be transmitted to the air so that:

$$Q_a \Delta p_a = Q_\ell \Delta p_n .$$

The subscript a is for air.

Test measurements indicated:[7]

$Q_\ell = 2 \times (9.2 \text{ gal/min}) = 2(0.58 \times 10^{-3} \text{ m}^3/\text{s})$
$\Delta p_n = 200 \text{ psig} = 12.8 \times 10^5 \text{ N/m}^2$
$Q_\ell \Delta p_n = 1.48 \times 10^3 \text{ W}$
$Q_a = 0.25 \text{ m}^3/\text{s} = 530 \text{ cfm}$
$\Delta p_a = 2.7 \times 10^2 \text{ N/m}^2 = 1.1 \text{ " } H_2O$
$Q_a \Delta p_a = 67 \text{ W}$

The difference is due to various losses and increases with increasing flow rates. Still, this represents a boost for the flow rather than a flow impediment.

COLLECTION EFFICIENCY

Test Procedure

The evaluation of the Dynactor scrubber was with respect to its mass collection efficiency as a function of particle size, the effect of several parameters on this efficiency, the air-moving capability and power consumption of the device, and its cost. Measurements included:

- Air flow and pressure gain versus spray nozzle pressure
- Electrical power consumption versus spray nozzle pressure
- Mass collection efficiency as a function of particle aerodynamic diameter at two levels of flow, temperature, and concentration, for two different dusts, in a balanced test matrix
- Mass collection efficiency as a function of particle size for several additional sets of conditions
- Total mass collection efficiency at the conditions noted above

Test Equipment

Most of the experimental work was done with the equipment shown in Figures 21 and 22. This equipment allowed measurement of collection efficiency as a function of particle size and the effects of differences in flow, concentration, temperature, and pressure drop which prevailed during the efficiency tests.

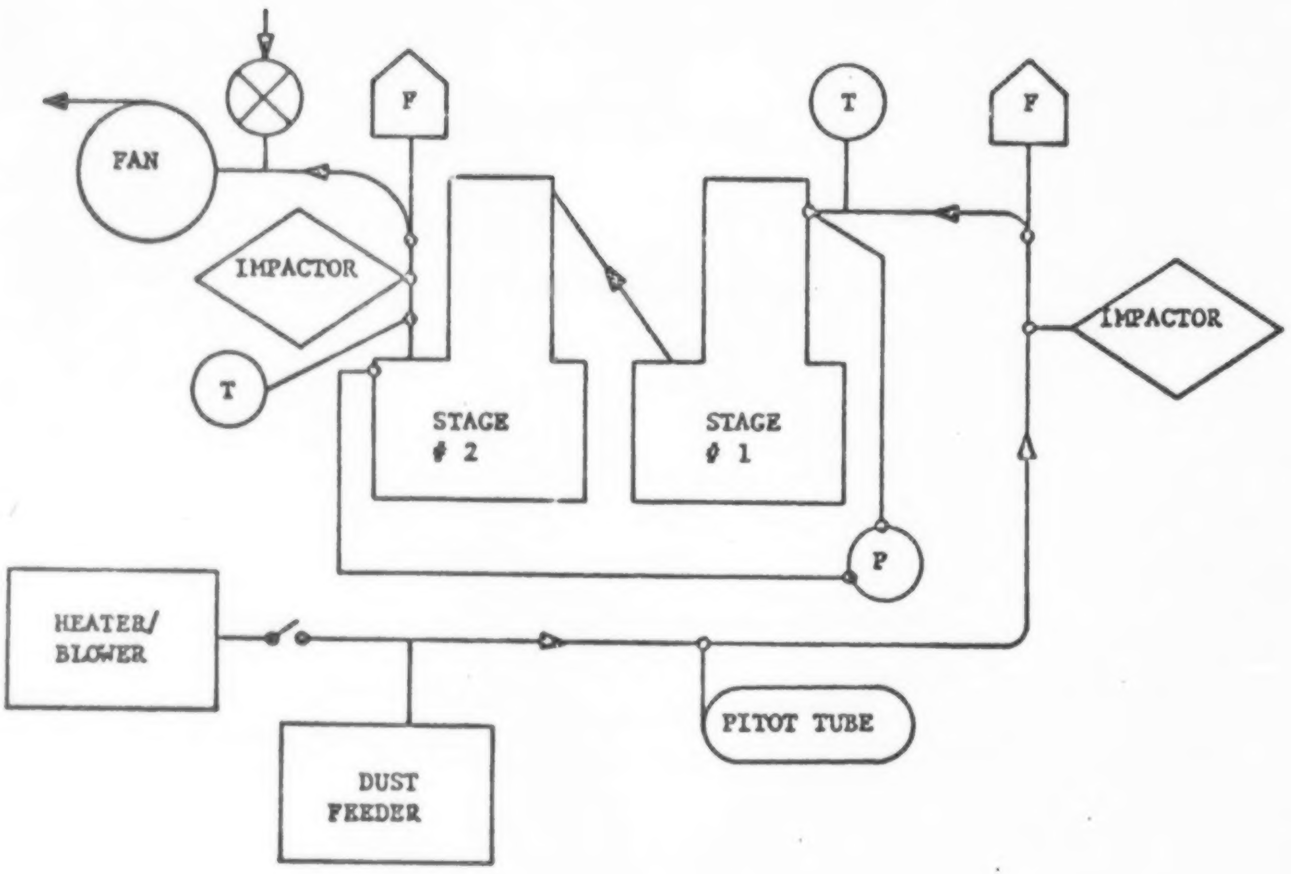

FAN
F
T
F
IMPACTOR
IMPACTOR
T
STAGE
# 2
STAGE
# 1
P
HEATER/
BLOWER
DUST
FEEDER
PITOT TUBE

Figure 21. Test system for Dynactor two-stage scrubber evaluation, including filter samplers (F), thermometers (T), and pressure gauge (P)

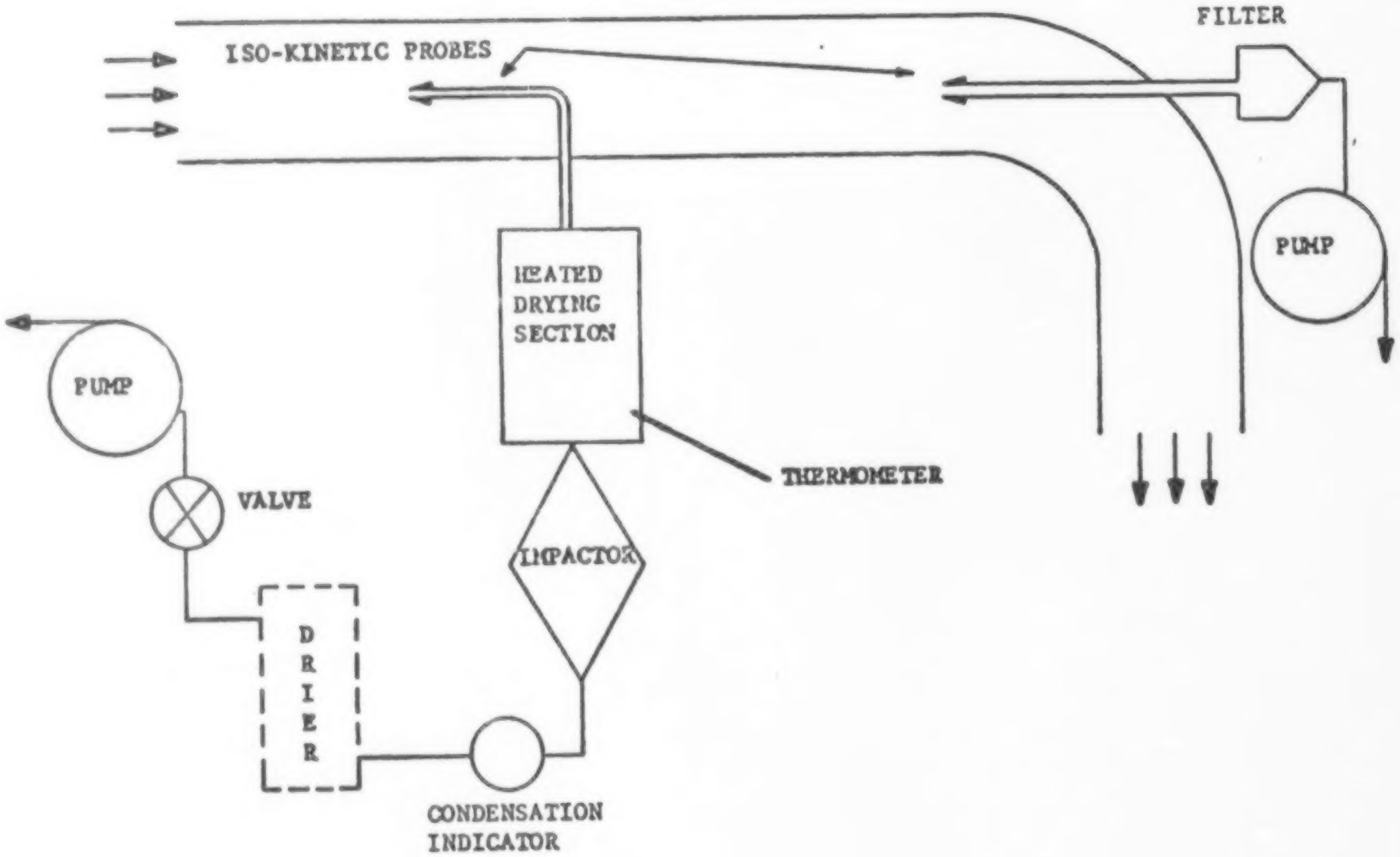

ISO-KINETIC PROBES
FILTER
PUMP
HEATED DRYING SECTION
THERMOMETER
IMPACTOR
CONDENSATION INDICATOR
D R I E R
VALVE
PUMP

Figure 22. Details of aerosol concentration and size distribution measurement sections

Figure 21 gives the overall picture of the test setup. Dust from a screw feed was picked up by an air ejector/aspirator and blown into ducting leading to the Dynactor.

Upstream, the turbulent mixture was sampled five or more duct diameters from the dust feed by a heated Andersen Model III cascade impactor, usually run with isokinetic flow, and by a filter assembly which always was operated isokinetically. An identical sampling combination was used downstream, as described more fully in Figure 22. The temperature and pressure of the mixture entering the Dynactor was measured as was, sometimes, the temperature of the mixture leaving the Dynactor. The pressure drop or gain across the device was measured. Upstream and downstream from the Dynactor, the Andersen Model III instack impactor was used to size-fractionate the aerosol. The impactors were used with the glass fiber media impaction substrates designed for them. The temperature of the impactor at the Dynactor outlet and its drying section (Figure 22) was kept about 20°C above the temperature of the Dynactor exhaust stream to produce drying of the droplets present in the exhaust. To obtain enough material on the downstream impactor for weighing and yet not too much material on the upstream impactor (to prevent rebound and reentrainment), it was necessary to run these impactors for different total durations, the downstream impactor sampling for about 10 times as long as the upstream impactor. The total filter samples had the same durations as their impactor counterparts. To prevent material from being captured by the probes upstream when a sample was not being taken, these probes were blocked with removable baffles. The concentrations were determined from weight changes in the filters and impaction substrates. Substrate material was dessicated before making the tare weighing as well as before making the weighing with the captured particulate material.

Test Results

Results are presented for collection efficiency, by mass, as a function of particle aerodynamic diameter. Sizing was done by using Andersen Model III In-Stack Impactors at 14 ℓpm flow rate (0.5 cfm), and the material on a given stage of the impactor was classified as being of an aerodynamic diameter greater than or equal to the aerodynamic cutoff diameter of the impaction stage and less than the aerodynamic cutoff diameter of the impaction stage immediately upstream. The cutoff diameter is the diameter for which the collection efficiency of the given impaction stage would be 0.50. The cutoff diameters were taken from information supplied by the impactor manufacturer.

Fractional Efficiency of Collection

A factorial test design was used to determine the Dynactor efficiency and the effects, if any, of flow rate, dust concentration, temperature, and dust type. The design allowed testing whether or not each of the parameters were significant, using standard analysis of variance, and allowed estimates of the experimental error of measurement.

The results of the factorial test are summarized in Table 5 and plotted on Figure 23. The mean efficiencies for the tests and the corresponding uncertainties are listed with the aerosol fraction to which they correspond. The aerosol fraction is either the size interval on the impactor stages or the total size range which reached the total filter.

Tables 6 and 7 present a much more detailed picture of the results of the efficiency tests. These are listed in Table 6:

- The aerosol fraction
- The mean of all the efficiency tests in the factorial design
- The means of the eight tests each at two different levels of flow, temperature, and concentration, and two different dusts

Table 5. SUMMARY OF RESULTS OF 16 COLLECTION EFFICIENCY TESTS FOR DYNACTOR (FACTORIAL TEST DESIGN)

Aerosol fraction	Mean efficiency	Number of tests, n	Estimated uncertainty ($\pm \sigma_e/\sqrt{n}$)
Total filter	96.04 %	16	± 0.32 %
Iron oxide	93.11	8	0.46
Fly ash	98.97	8	0.46
2.5 - 4.0 μm	98.37	16	0.12
1.3 - 2.5 μm	93.00	16	0.21
0.8 - 1.3 μm	75.4	16	2.1
0.54 - 0.8 μm	27.4	16	6.6
≤ 0.54 μm	47.4	16	3.7

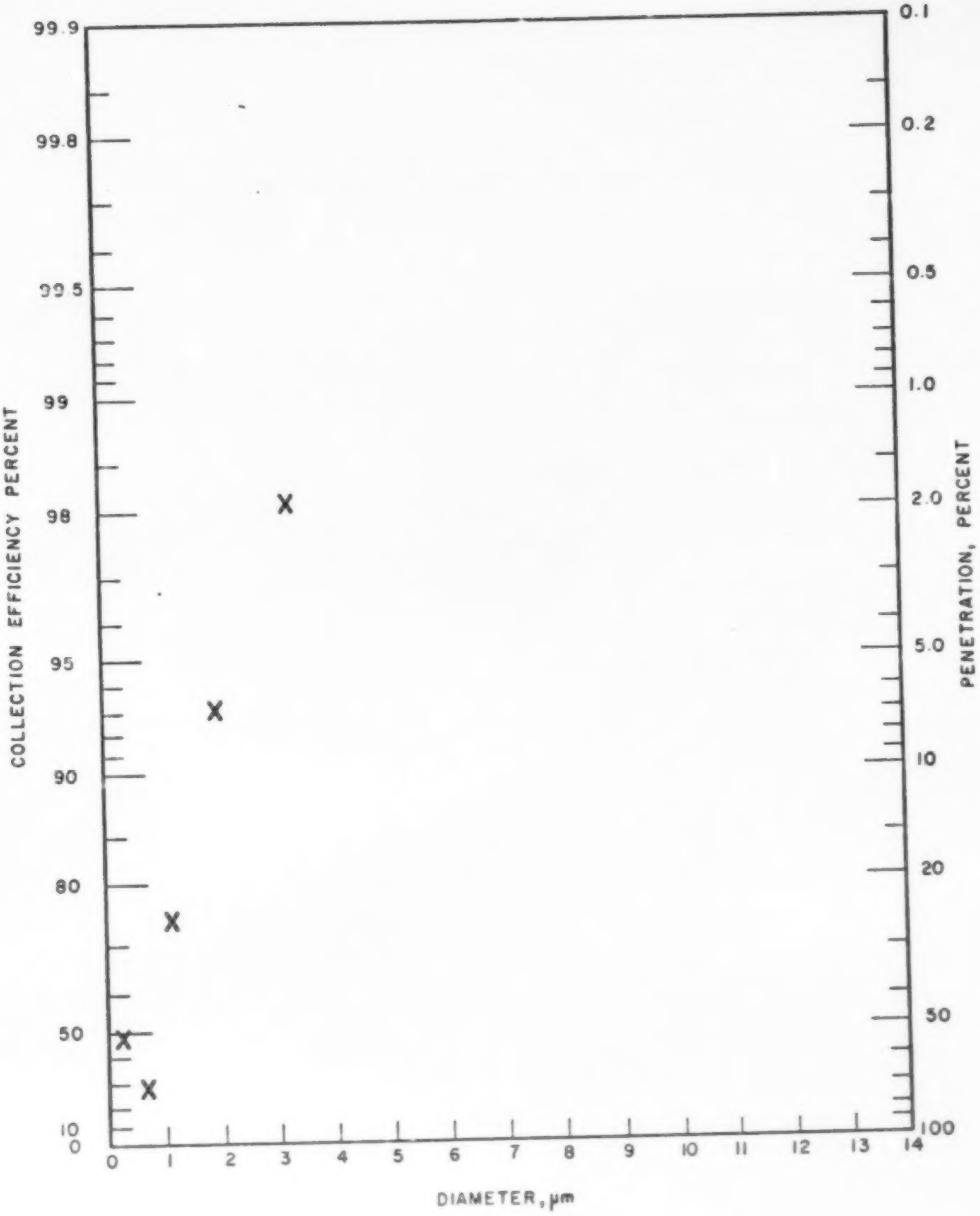


Figure 23. Summary of results of 16 collection efficiency tests (factorial design)

Table 6. EFFICIENCY AVERAGES VERSUS PARTICLE AERODYNAMIC DIAMETER

Aerosol fraction	Flow, m^3/s (cfm)		Dust		Temperature		Concentration		
	0.24 (500)	0.47 (1000)	Fly ash	Iron oxide	Ambient, 20°C	Hot, 95°C	High, ~ $1 g/m^3$	Low, ~$0.1 g/m^3$	Grand mean
Total filter	96.69	95.40	98.97	93.11	96.50	95.59	97.21	94.87	96.04
Total impactor	94.05	93.36	97.60	89.81	94.40	93.01	95.79	91.62	93.71
2.5 - 4.0 μm	98.75	97.99	99.26	97.47	98.57	98.16	98.74	98.00	98.37
1.3 - 2.5 μm	94.82	91.17	93.62	92.37	93.54	92.46	93.41	92.59	93.00
0.8 - 1.3 μm	83.45	67.44	69.01	81.87	78.95	71.94	78.10	72.79	75.44
0.54 - 0.8 μm	26.66	28.12	37.86	16.92	25.04	29.75	28.27	26.51	27.39
≤ 0.54 μm	49.26	45.50	54.82	39.94	51.36	43.40	71.25	23.51	27.38

Table 7. SIGNIFICANCE OF EFFECTS OF FLOW, DUST, TEMPERATURE, AND CONCENTRATION ON SCRUBBER COLLECTION EFFICIENCY

	Significance level			
Aerosol fraction	Flow	Dust	Temp.	Conc.
Total filter	~ 0.90	> 0.99	--	> 0.95
Total impactor	--	> 0.99	> 0.99	> 0.99
2.5-4.0 μm	> 0.95	> 0.99	--	> 0.95
1.3-2.5 μm	> 0.99	> 0.95	> 0.95	~ 0.90
0.8-1.3 μm	~ 0.90	--	--	--
0.54-0.8 μm	--	--	--	--
≤ 0.54 μm	--	~ 0.90	--	> 0.99

Table 7 shows whether these differences are statistically significant as a result of the standard F-test analysis of variance. The analysis of variance allows one to determine what likelihood there is that the differences noted between measurements come from differences in the parameters under study rather than from extraneous variations. The "significance level" is the probability that one would be correct in ascribing a difference in the results to a difference in the level of the parameter under test, here flow, dust, temperature, and concentration, making the usual statistical assumptions about normal populations. The above information in Tables 6 and 7 allow the following conclusions:

1. The lower flow rate yielded higher efficiencies for all size fractions and the differences were usually statistically significant.
2. Fly ash was collected with greater efficiency than iron oxide for all but one size fraction, and these differences were usually statistically significant.

3. The lower temperature produced greater efficiencies than did the higher temperature, in seven of eight aerosol fractions, but this was statistically significant in only two fractions.
4. Higher concentrations were collected with greater efficiency than lower concentrations and this was statistically significant in most fractions.

Discussion of Experimental Results

As noted in the results, there were statistically significant effects on collection efficiency due to flow, dust, temperature, and concentration of particulates. These effects are discussed and linked with results of others.

Flow

Increasing the flow rate will increase the velocity gradients, which would be expected to increase deposition due to impaction and interception and to increase the turbulent eddy diffusivity, which is a linear function of the Reynolds number (Calvert et al.[8]) and thus increase the rate of mass transfer to the droplets. Increasing the flow rate will also decrease the residence time, which would give less time for the collection mechanisms to act, significant for the smallest particles, where diffusion would predominate the collection mechanisms, and for the largest particles, for which settling would become important. Somewhat higher collection efficiencies at the lower flow rate were found, as Lancaster and Strauss[9] found in their experiments with spray scrubbers, using ZnO particles with a number median diameter of 1.0 μm.

Dust

Particles of fly ash were generally collected with greater efficiency than particles of iron oxide having the same aerodynamic diameter in our tests. Different aerodynamic behavior by particles having the same aerodynamic diameter is unexpected, but perhaps the particles differed in the likelihood with which a particle/droplet collision produced capture or in the degree to which they served as nuclei during condensation or the degree to which high humidities facilitated their agglomeration. The iron oxide powder seemed less hydrophilic than did the fly ash, because water droplets beaded up on iron oxide layer and absorbed into a fly ash layer, thus the iron oxide may have been less wettable and more difficult for the water droplets to entrap. Lohs[10] found that making hydrophobic polystyrene particles into hydrophilic ones, by coating their surfaces with a wetting agent, increased the capture of these particles by a spray scrubber. From their experiments with venturi scrubbers, Calvert, Lundgren, and Mehta[11] concluded that particle wettability enhanced collection efficiency.

Temperature

Temperature can influence collection efficiency in a variety of ways. Higher temperatures means higher viscosity for gases; for example, as air goes from 20°C to 100°C, its viscosity increases a factor of 1.20 (Bird et al.),[12] which increases its resistance to particle motion, hindering the various collection mechanisms. For the submicron particles, this can be offset by the increases in the particle diffusivity due to Brownian motion. Our experiments showed a statistically significant decrease in collection efficiency for 1.3-2.5 μm aerodynamic diameter particles as temperature increased from 20°C to 95°C, as well as a general trend toward decreased efficiencies for all the aerosol size fractions. Lancaster and Strauss[9] measured a decrease in efficiency in going from 20°C to 30°C with a spray scrubber operating on water-saturated air containing particulate material.

Concentration

As particle concentration increases, particle agglomeration increases due to coagulation. Increased agglomeration means an aerosol having larger mean size, which generally enhances collection efficiency in spray scrubbers. Increased concentrations yielded higher collection efficiencies in all the aerosol size fractions in our tests. Lancaster and Strauss,[9] among others, reported increased efficiency with increased mass loading. In the tests with the Dynactor, the improvement in collection was most dramatic for the smallest particles, indicative of coagulation.

Water Vapor Addition

A discussion of the net effect that diffusiophoresis and thermophoresis have in this type of system is included in the GCA study,[7] but is omitted here because the water vapor addition tests with the Dynactor were inconclusive.

POWER CONSUMPTION

The Dynactor tested used two high-pressure pumps to supply the spray nozzles. Measurements showed the total power consumed by both pumps was 4.6 kW ≅ 6.2 hp regardless of nozzle pressure. A basic estimate of power consumption, expended by the nozzles, is the product of pressure drop across the nozzles and the volume rate of water flow, which equaled 1.48 kW (2.00 hp) for the highest pressure drop (200 psig). Thus, the efficiency of the pumps was 35 percent, but larger models with larger pumps are expected to yield 60 - 70 percent efficiency. At 60 percent power efficiency, the power consumption would be 3.3 hp/1000 cfm = 5.2 kW/(m^3/s).

WASTE DISPOSAL

Waste water from the Dynactor may be treated the same way as waste water from any other scrubber. RP Industries manufactures settling basins and high rate settling columns for use with their scrubbers when solids loading is heavy. Waste disposal is treated in Section XIV on costs.

SECTION IX

LONE STAR STEEL STEAM-HYDRO SCRUBBER

MANUFACTURER'S DESCRIPTION[13]

"The system utilizes a high-speed steam drive with injected water to perform an extremely efficient scrubbing action. The heart of the system, which contains no moving parts, consists of a steam nozzle, water injector, mixing tube and twin cyclones. System operation is simple and easily controlled.

"Normally, the system operates on energy produced by waste heat captured from the process being controlled. The heat is used to generate steam in a waste heat boiler. In installations where heat energy is low, supplemental heat may be provided. In many cases, a package steam boiler may supply all the energy.

"In addition to driving the system, the steam nozzle creates draft which draws contaminated gases into the system.

Atomizer Chamber

"First stage of cleaning is done in an optional atomizing chamber with water sprays that may be employed to cool the gas stream and remove heavy particulate. Most processes do not require this chamber but it can be installed as a first-phase cleaner for certain difficult effluents. A negative pressure is maintained in this chamber. A process occurs where steam joins small particulate for second-phase removal in the mixing tube.

Mixing Tube

"Collision between injected water droplets and the particulate (including acidic gases if present), encapsulation, nucleation, and droplet growth take place in the mixing tube. Collisions occur between particulate and billions of high-speed water droplets. Particulate is encapsulated and a growth process begins to bring submicron particulate to manageable size for disposal through low-pressure-drop cyclones. To insure positive capture of all particulate, a shock wave pattern is created in the mixing tube. Massive turbulence created by the shock wave pattern subjects encapsulated particulate to a sudden and violent scrubbing action".

Cyclones

"Separation of particulate from the gas is achieved by entering low-pressure-drop cyclones with appropriate velocities and particulate which has grown to a size matched to the system. Centrifugal energy in the cyclones is maintained by force imparted from the mixing tube."

Figure 24 shows the Lone Star Steel Steam-Hydro Air Cleaning System, from the Southern Research Institute (SoRI) evaluation.[13]

POTENTIAL APPLICATIONS

The Steam-Hydro system, manufactured and marketed by Lone Star Steel, provides >99 percent collection efficiency over a wide range of particle size, those >0.3 μm. However, intrinsic power consumption is quite high, an order of magnitude greater than an ejector venturi scrubber. If fuel must be purchased to make the steam, the Steam-Hydro system is not an economic alternative to such systems as fabric

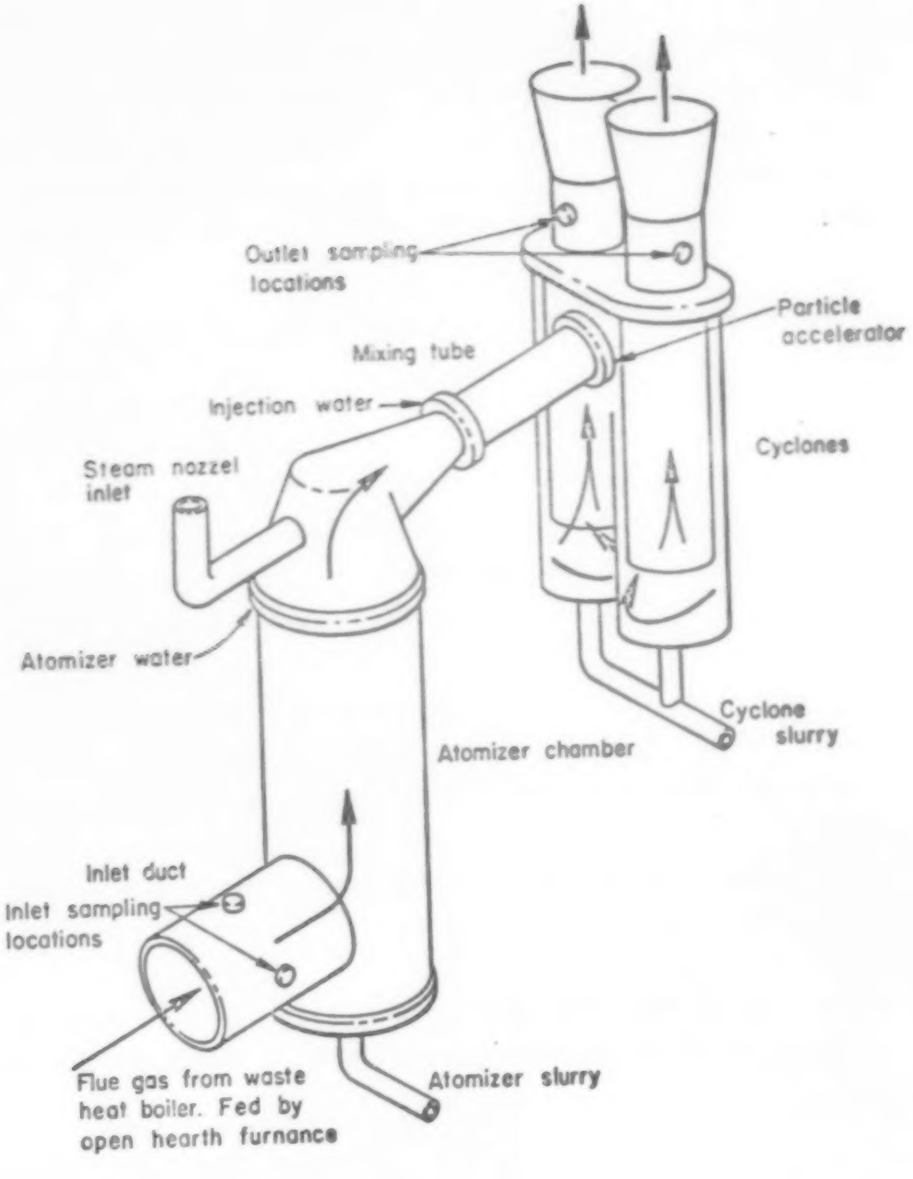

Outlet sampling locations
Particle accelerator
Mixing tube
Injection water
Cyclones
Steam nozzel inlet
Atomizer water
Cyclone slurry
Atomizer chamber
Inlet duct
Inlet sampling locations
Flue gas from waste heat boiler. Fed by open hearth furnance
Atomizer slurry

Figure 24. The Lone Star Steel steam-hydro air cleaning system[13]

filtration or electrostatic precipitation. If sufficient waste heat is available, the Steam-Hydro system becomes economically feasible. It should be noted that this system creates its own draft, thus obviating the need for fans, blowers, etc. The Steam-Hydro system has been installed in open hearth furnaces, cupolas, iron ore kilns, paper mills, sinter plants, ammonium nitrate fertilizer plants, and copper smelters. Other possible application sites are basic oxygen furnaces, electric arc furnaces, lime and cement kilns, and municipal incinerators.

Particle Characteristics

Particle Size - The SoRI study reports very high collection efficiency for sizes down to about 0.5 μm, with a minimum efficiency of 70 percent at around 0.05 μm (based on diffusional results). The Steam-Hydro system can be expected to clean particulate laden gas streams to high efficiency (about 99.9 percent for the SoRI test with 1.8 μm mass median aerodynamic diameter aerosol) unless the particulate is extremely fine.

Particle Phase - Solid or liquid particles are expected to be collected equally well. The manufacturer indicates that vapors can be effectively controlled with additional energy input.

Resistivity - Particle resistivity is not expected to influence collection efficiency.

Abrasiveness - The Steam-Hydro system appears well suited to controlling abrasive aerosols because of the absence of moving parts, fabric filters, etc.

Corrosiveness

Steam-Hydro systems have been built from stainless steel, carbon steel, coated materials, and fiberglas. Difficult materials handling problems can presumably be solved by choosing proper construction material.

Gas Characteristics

Volume Rate of Flow - Modules can be designed to handle from about 2 m^3/s (4×10^3 scfm) to 150 m^3/s (3×10^5 scfm).

Temperature - An optional atomizing chamber with water sprays may be employed to cool the gas stream and remove heavy particulate. With the proper wasteheat boiler, even the highest temperature industrial gas streams may be cleaned.

Flow Velocities, Magnitudes, and Variations - There are three controls for the Steam-Hydro system, the proper adjustment of which should provide maximum collection efficiency. These are steam pressure at the ejection nozzle inlet, gas flow rate, and cyclone accelerator position. The first two adjustments are self-explanatory and the last determines flow pattern in the cyclone to affect maximum droplet removal.

Stack Characteristics

A most important consideration towards deciding if a Steam-Hydro system should be installed is the availability of steam. If waste heat boilers are already in use for a certain process, significant capital expense will be saved. In a given situation, the Steam-Hydro system will probably not require all the steam that is generated. For example, the SoRI study of the Lone Star Steel open hearth operation found that the Steam-Hydro system used 0.92 kg/s (7300 lb/hr) of 18×10^5 N/m^2 (250 psig) saturated steam, whereas a single open hearth may provide as much as

42 kg/s (150,000 lb/hr). Given that steam is available, ducting and space requirements should not be much different for the Steam-Hydro system compared to other alternatives such as venturi scrubbers, and should be less than fabric filtration units (bag houses). Another variable worth mentioning is the operating condition of the waste-heat boilers. If the waste heat boilers are not designed so that they can be kept clean the steam requirement is greater to overcome the resistance caused by particulate buildup in the heat transfer sections. A dirty waste heat boiler will not be as efficient for heat exchange as well.

THEORY OF OPERATION

The scrubber uses high pressure steam to move the gas through the system through eduction. The rapidly moving steam entrains gas, particles, and droplets. The particles collect on the droplets by mechanisms described in our section on the general theory of obstacle collectors; the principal mechanism is believed to be impaction for particles larger than a few tenths micron. Diffusion and the condensation of the steam onto the droplets (entraining particles) are also thought to be significant. Once the particles have collected on the droplets, the drop/particle mixture is caught in the centrifugal collectors (cyclones) immediately downstream from the scrubber mixing section. The energy required to move the gas, particulates, and droplets through the system is supplied not by fans or pumps but by steam produced in boilers or economizers operating on the waste heat of the process. The wastewater sludge effluent from the cyclones must be handled as other scrubber waste water is.

Collection Efficiency

Southern Research Institute conducted tests on the Steam-Hydro system; excerpts from their report are in quotation marks. Their report[13] is our basic source for the Lone Star Steel system. "A total of four measurement techniques were used during the tests. These were: (1) diffusional techniques using condensation nuclei counters and diffusion batteries for determining concentration and size distribution on a number basis for particles having diameters less than approximately 0.2 μm, (2) optical techniques to determine concentrations and size distribution for particles having diameters between approximately 0.3 μm and 1.5 μm, (3) inertial techniques using cascade impactors for determining concentrations and size distributions on a mass basis for particles having diameters between approximately 0.25 μm and 5 μm, and (4) standard mass train measurements for determining total inlet and outlet mass loadings."

"The useful concentration ranges of both the optical counter and the condensation nuclei counters are such that extensive dilution of the gas streams being sampled was required. Dilution factors of about 65:1 were used for the outlet measurements and about 500:1 for the inlet measurements. In order to insure that condensation effects were minimal and that the particles were dry as measured, the diluent air was dried and filtered, and diffusional driers were utilized in the lines carrying the diluted samples to the various instruments."

"Because of the size and complexity of the optical and diffusional measuring systems, and the fact that only one set of equipment exists for measurements of this type, it was not possible to obtain simultaneous inlet and outlet data with these methods. The system was first installed at the outlet sampling location, the scrubber was tuned, and all the outlet data were obtained. Subsequently, the equipment was moved to the inlet and the necessary inlet data were obtained. For the purposes of calculating the efficiency of the scrubber, the assumption was made that the open hearth process was sufficiently repetitive that the inlet data, as obtained above, were a valid representation of that which would have been obtained during the time the outlet measurements were made. Accuracy in the diffusional measurements was limited by process variations and the efficiencies derived from these data are rather uncertain. However, the trends in the fractional efficiencies derived from the data are probably real and the fractions of the influent material that penetrate the scrubber are probably correct to within a factor of two to three."

"The optical data are presented on the basis of equivalent polystyrene latex sizes and the indicated sizes can differ from the true sizes by factors as large as two to three. Data obtained using this method were primarily intended as a means of real time monitoring of process changes and the results of changes in the scrubber operation, but also serve as rough checks on the data obtained with the cascade impactors. The sampling system used for obtaining the optical and diffusional data is illustrated diagrammatically in Figure [25]."

The investigators reported that the use of the rapid-response instruments, the condensation nuclei counter and the optical counter, facilitated optimization of the operating parameters.

The tests were difficult for a number of reasons, requiring several engineering compromises. The great disparity between the inlet loadings (about 1 $gr/ft^3 = 2.3\ g/m^3$) and the outlet loadings ($\sim 0.02\ g/m^3$) meant that two different impactor types were used, a Brink impactor upstream and an Andersen in-stack impactor downstream. Furthermore, the sampling times were very different, about 6 hours downstream and 6 minutes upstream. Only one set of the equipment, shown in Figure [25] was available, so that upstream and downstream sampling were done at different times, average size distributions being obtained for comparison from measurements at various stages in the process. Large and rapid concentration fluctuations added uncertainty to the average values obtained from the short-term samples for total mass measurement, impactor sizing, optical sizing, and diffusional sizing.

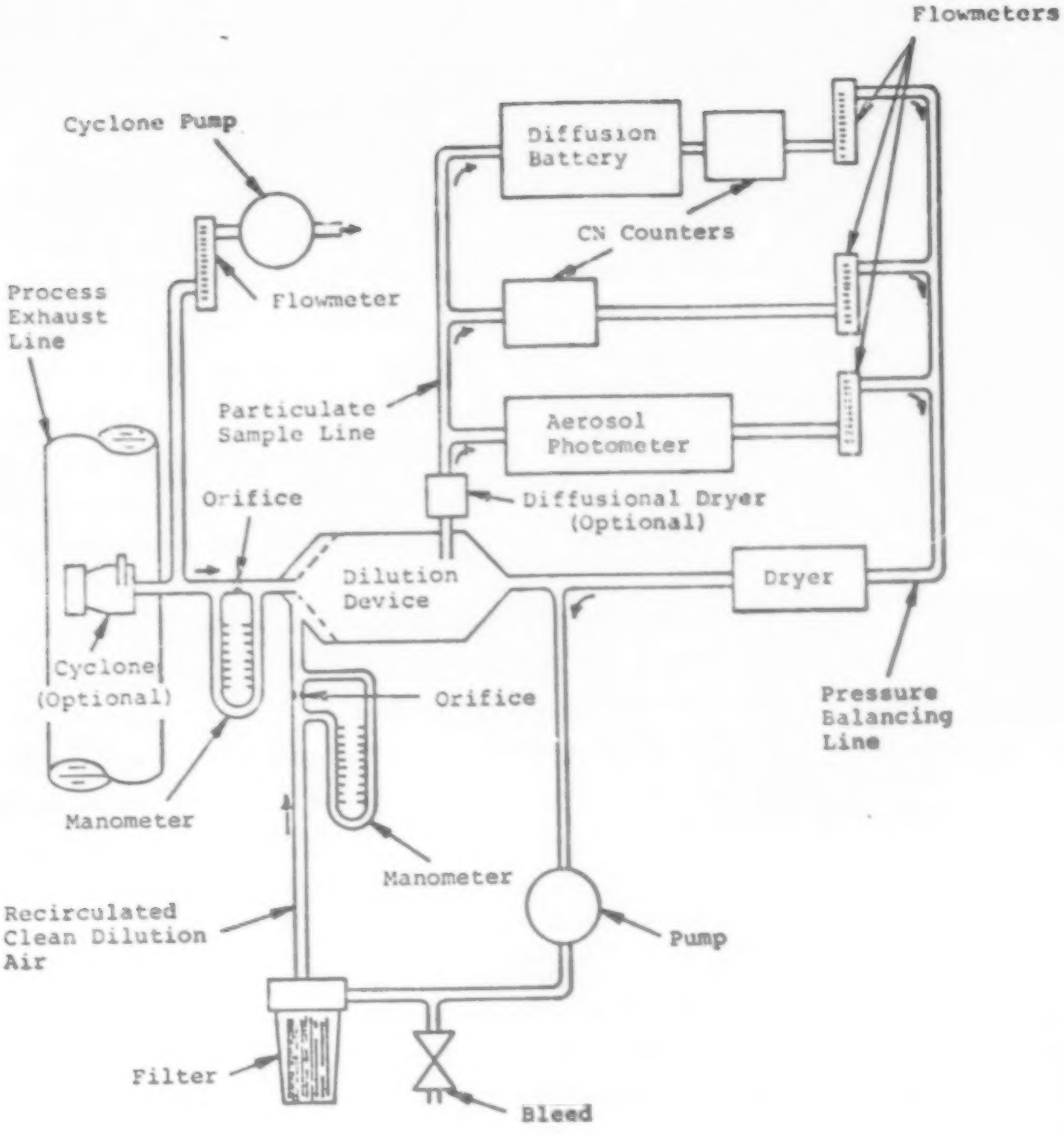

Flowmeters
Cyclone Pump
Diffusion Battery
CN Counters
Process Exhaust Line
Flowmeter
Particulate Sample Line
Aerosol Photometer
Orifice
Diffusional Dryer (Optional)
Dilution Device
Dryer
Cyclone (Optional)
Orifice
Pressure Balancing Line
Manometer
Manometer
Recirculated Clean Dilution Air
Pump
Filter
Bleed

Figure 25. Optical and diffusional sizing system[13]

"Inertial sizing was accomplished using Brink cascade impactors for inlet measurements and Andersen impactors for outlet measurements. Sampling was done at near isokinetic rates. Errors due to deviations from isokinetic sampling should be of little consequence for particles having aerodynamic diameters smaller than 5 μm or physical diameters smaller than 2 μm for an assumed density of 5.2 gm/cm^3. Further, because the sampling was at near isokinetic rates, the calculated collection efficiencies for larger particles are probably reasonably close to the true values. Because of the relatively small duct dimensions as compared to the sizes of the impactors, single point sampling was used in the ducts with the inlet impactors at flue gas temperature (515°F). The outlet impactors were heated to about 40° above flue gas temperature to insure that no condensation took place within the impactor. Such condensation might cause operational difficulties or lead to incorrect sizing."

In Figure 26 are shown the inlet and outlet size distributions obtained by measurements during the oxygen lance part of the process cycle. The instruments used were the optical counter and the diffusion battery plus condensation nuclei counter combination, giving optical equivalent diameters and mobility equivalent diameters, respectively. These measurements were combined with the impactor measurements to give efficiency as a function of particle geometric diameter, shown in Figure 27, on the assumption that the dust had a density of 5.2 gm/cm^3.

Figure 28 shows fractional efficiency using impactor data only, adjusted to aerodynamic diameter. The points are for optimum Steam-Hydro operating parameters (cyclone accelerator position, steam pressure, and gas flow). The relationship used to go from Figure 27 to Figure 28 is

$$d_{ae} = \sqrt{\frac{C_p \rho_p d_p^2}{C_{ae} \rho_o}}$$

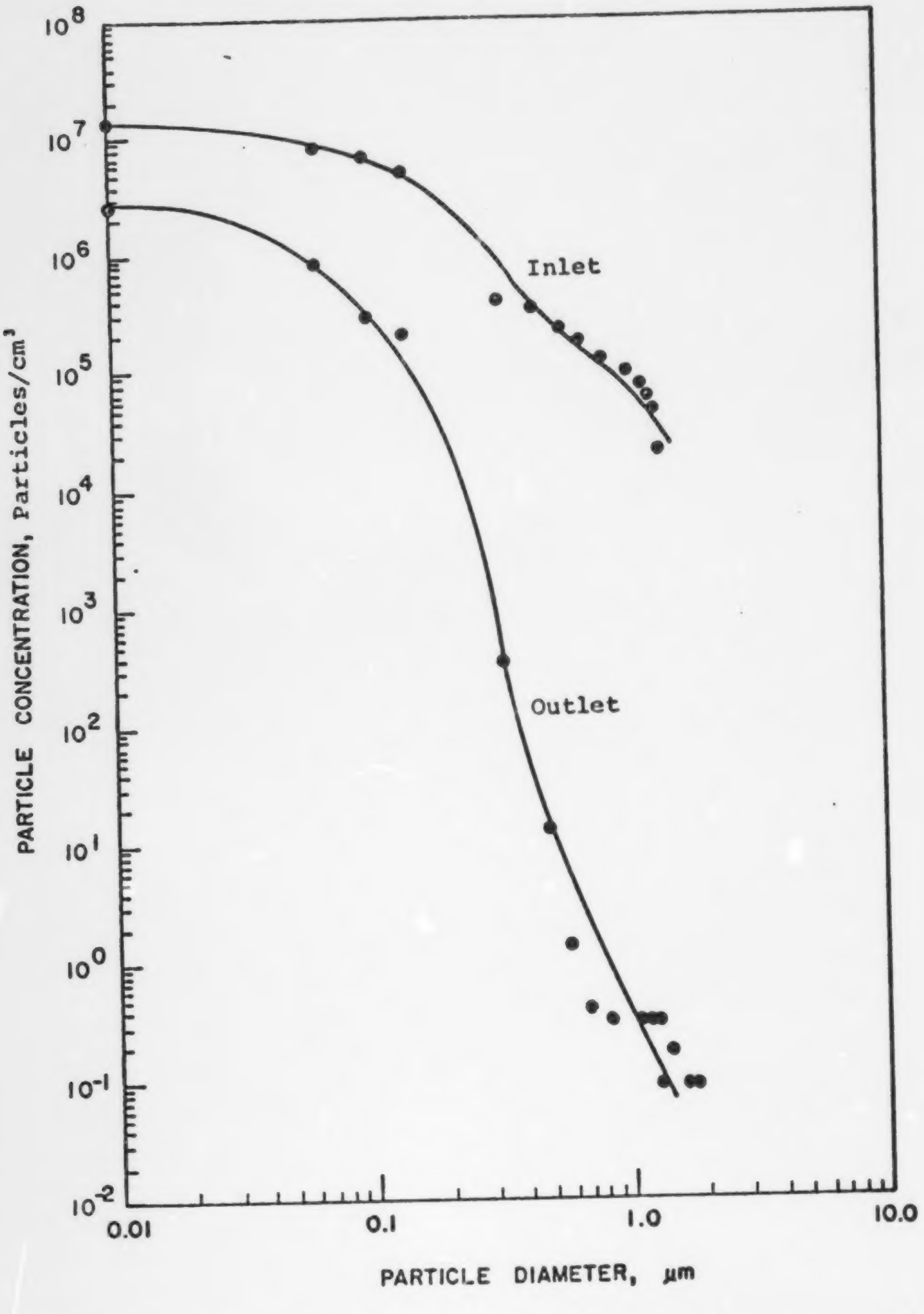


Figure 26. Inlet and outlet particle size distributions measured using optical and diffusional techniques[13]

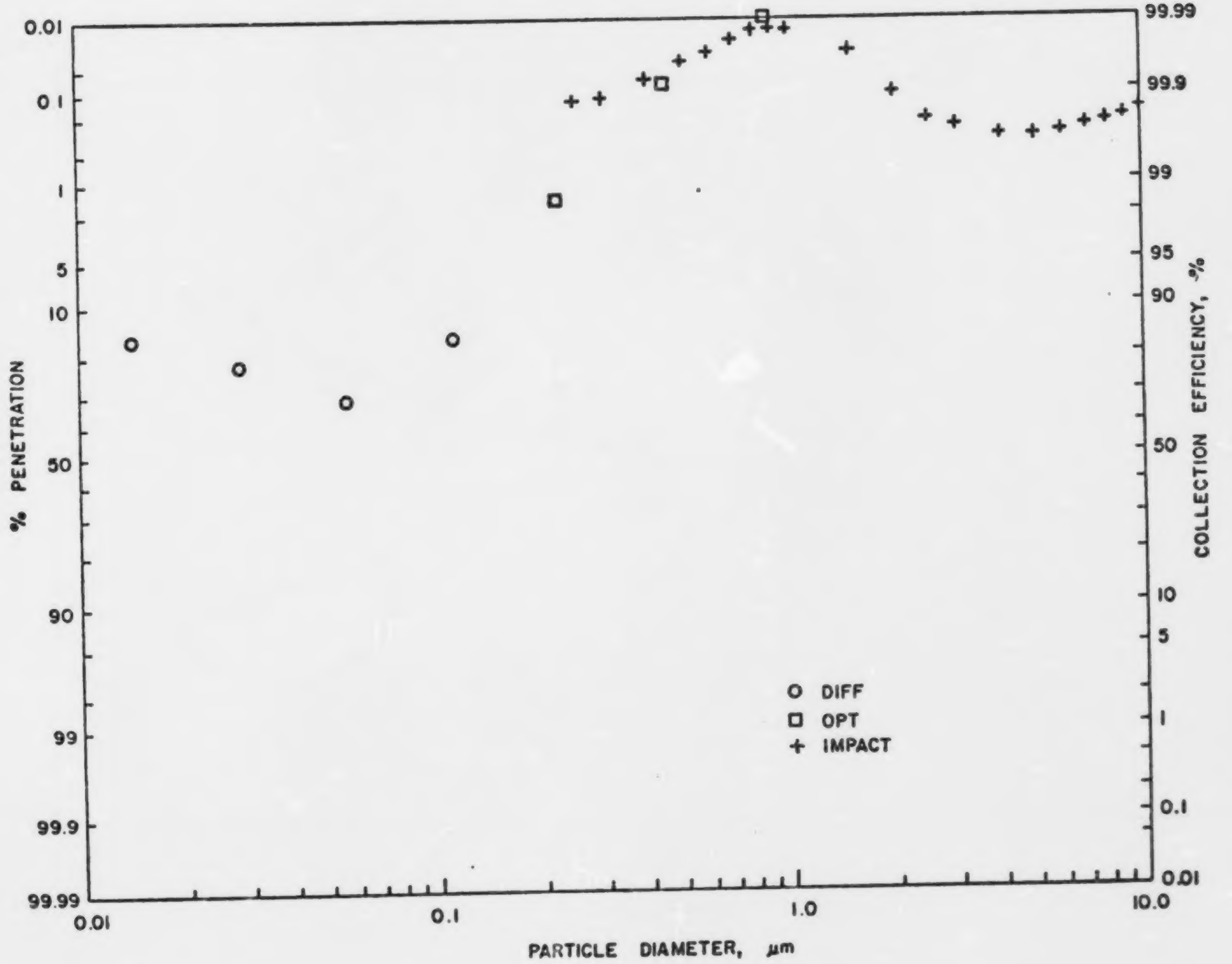


Figure 27. Fractional efficiency of the Lone Star Steel Steam-Hydro Scrubber[13]

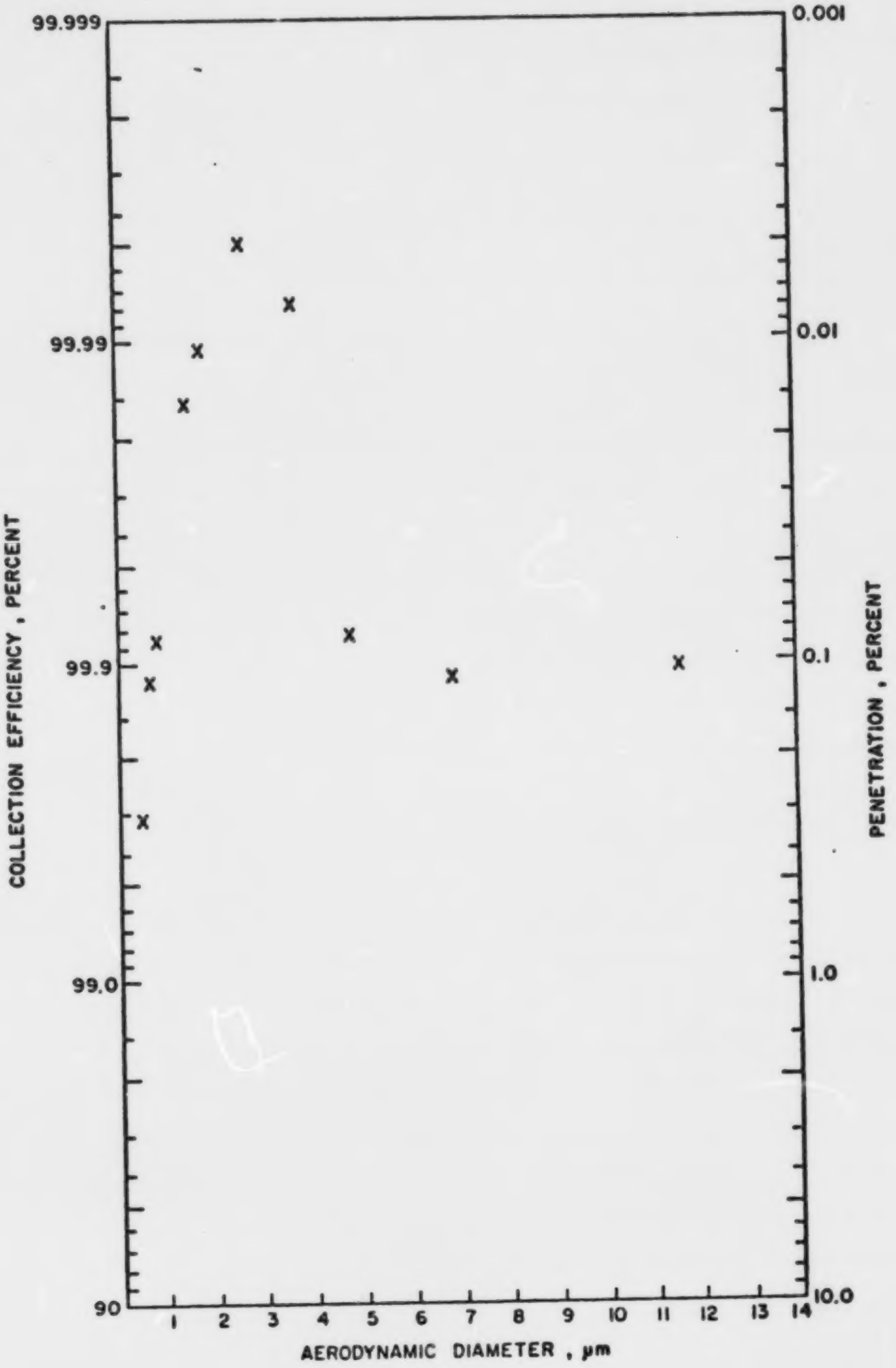


Figure 28. Collection efficiency versus aerodynamic diameter, Lone Star Steel Steam-Hydro Scrubber

where d_{ae} = aerodynamic diameter

C_p = Cunningham factor for particles in test

ρ_p = density of test particles, 5.2 g/cm^3

ρ_o = density of water, 1.0 g/cm^3

d_p = reported diameter (from Figure 27)

C_{ae} = Cunningham correction factor for aerodynamic diameter particle.

An iterative solution was used. Aerodynamic diameter is more fully discussed in the Appendix.

Mass train measurement obtained by Guardian Systems, Inc. of Anniston, Alabama under subcontract to SoRI showed an average collection efficiency of 99.86 percent for 9 tests, with a range of 99.78 percent to 99.95 percent. Inlet mass median aerodynamic diameter was calculated to be 1.8 μm from SoRI Brink impactor data.

POWER CONSUMPTION

Energy requirements to achieve various outlet loadings are plotted on Figure 29 as calculated by the manufacturer. Energy used in the SoRI study to achieve outlet loadings consistently less than 0.002 g/m^3 (0.001 gr/scf) were 395×10^3 J/kg calculated as (170 Btu/lb) of air from the manufacturer's estimate of 475×10^3 J/m^3 (12,750 Btu/1000 SCF) for a system back pressure of 15.2 cm H_2O (6 in. H_2O), and 348×10^3 J/m^3 (150 Btu/lb) of air from the test conditions of 0.92 kg/s (7300 lb/hr) of 1.72×10^3 N/m^2 (250 psig) saturated steam and 6.1 m^3 (13,000 scfm). Therefore, the point on Figure 29 denoted by an asterisk has been experimentally verified.

One scale has been added to the right hand side of Figure 29 to show equivalent electric energy in hp/1000 scfm, another for kW-hr/1000 scf. Note that 1 hp/1000 scfm equals 1.58 $kW/(m^3/s)$.

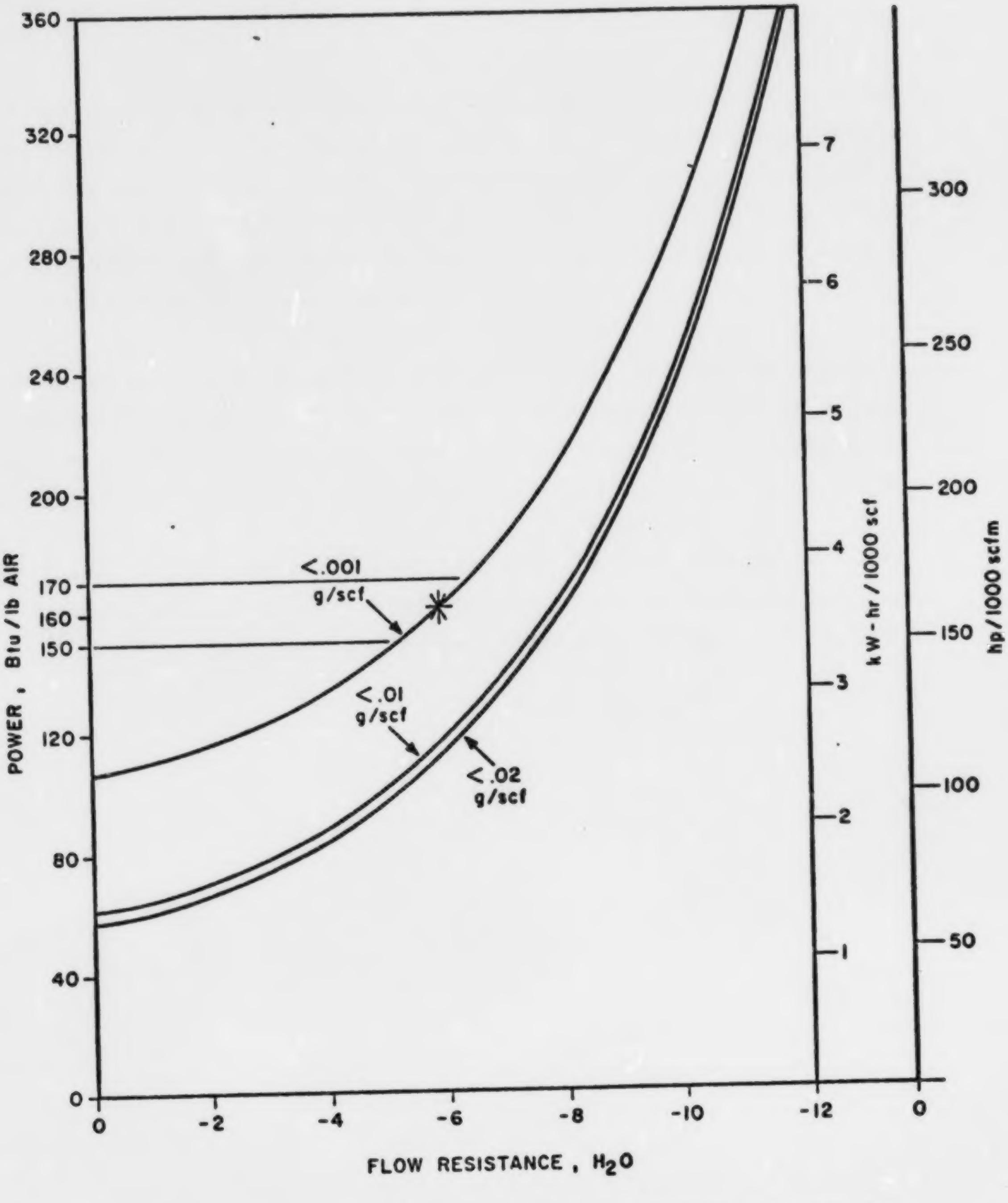


Figure 29. Power consumption versus flow resistance for Lone Star Steel Steam-Hydro Scrubber[13]

WASTE DISPOSAL

The waste generated from the Steam-Hydro system is a wet slurry and reference should be made to the section on wastewater disposal for better understanding of the problems involved. For the case of the open hearth operation studied by the SoRI, a clarifier was used to drop the solids concentration to less than 50 ppm and the waste was lime treated to reduce acidity caused by SO_2 collection. Most waste water is recirculated.

A notable consideration of this system used at the Lone Star Steel open hearths is the fact that zinc recovery from the wet slurry is enough to provide zinc requirements for the entire galvanizing operation at that plant and is valued at $1-1/2 million per year. Lead is also recovered.

Lone Star Steel reports that the high collection efficiency, especially at small particle size, of the Steam-Hydro system makes ZnO recovery greater than recovery from other lower-energy cleaning systems.

SECTION X

MYSTAIRE SCRUBBER

This section is based upon the theoretical evaluation[14] done by Midwest Research Institute (MRI) of the Mystaire™ scrubber, manufactured by Heat-Systems Ultrasonics, Inc. of New York.

DESCRIPTION

Details of the Mystaire scrubber construction are proprietary. Sketchy information is available from the manufacturer and some further information has been developed by MRI and by GCA/Technology Division. Figure 30 shows a bench-scale model of the device. Air containing particulate and/or gaseous contaminants enters the scrubber, passing through a spray and traversing a multi-layer wetted wire mesh screen, the Waterweb™. Gases are captured to an extent in the wetted screen by diffusion, and particulate material is caught by impaction, interception, and diffusion, as outlined in the section in this document on general theory of particle capture. The captured material is drawn off by the drains and removed from the water, some of which may be recirculated.

POTENTIAL APPLICATIONS

This device is similar to scrubbers in that much of the particle and gas capture will be occurring on water surfaces having dimensions of the order of 10^2 μm. To the degree that the captured material is indeed removed by the water flow, the waste disposal situation will be very similar to that of scrubbers. It differs from filter systems primarily in the method

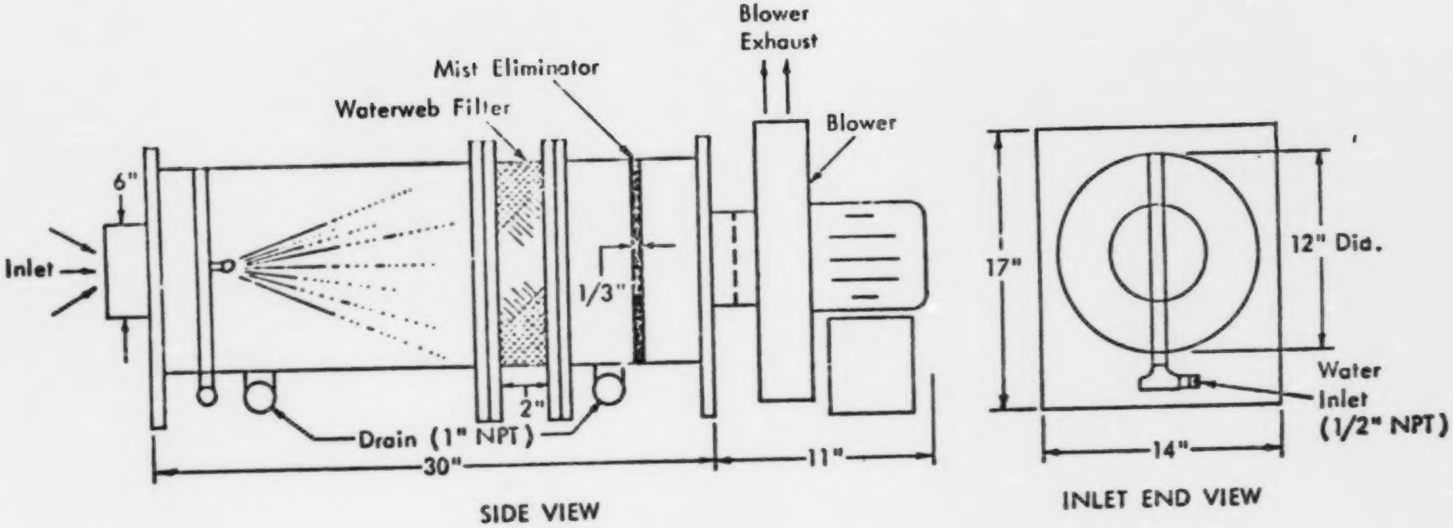

Blower
Exhaust
Mist Eliminator
Waterweb Filter
Blower
6"
Inlet
1/3"
2"
Drain (1" NPT)
30"
11"
SIDE VIEW
17"
12" Dia.
Water
Inlet
(1/2" NPT)
14"
INLET END VIEW

Figure 30. Schematic diagram of the Mystaire^{TM} Laboratory Scrubber[14]

of cleaning (by water rather than by the dislodgement of material caught on dry fibers). Pressure drop is much more like that for fabric filters than it is for scrubbers with comparable efficiencies, thus power savings could result.

The promotional literature notes: "The Mystaire scrubber has proven successful through field installation or independent laboratory testing on the following 'difficult' pollutants: H_2S, SO_2, NO_2, hydrofluoric acid, bacteria, ammonium chloride, titanium tetrachloride, formaldehyde, paint bake oven fumes, food processing odor, and mineral oil fumes."

Particle Characteristics

Particle Size - The MRI evaluation predicted particle collection efficiencies of 94 percent for particles of diameters 0.5 and 1.0 μm, with efficiencies of 99.9 percent for particles larger than 3 μm or smaller than 0.1 μm. As discussed in the following sub-section, we have arrived at somewhat lower efficiency predictions, with a minimum in the same range.

Particle Phase - Liquid particles presumably would be more readily carried off than solid particles in the water flow which cleans the filter mat. With solids, the development of dry spots and the buildup of material thereon, if it occurred, could be quite problematic. Water soluble solids should also be easily removed from the mesh. Solid particles have been successfully treated with the Mystaire scrubber, its makers report, and we have no information to the contrary.

Resistivity - This should have no effect upon performance.

Abrasiveness - The device does not employ relatively high velocities, thus abrasion is lessened.

Corrosiveness - Successful application for $TiCl_4$ and for hydrofluoric acid indicates corrosive materials can be handled.

Gas Characteristics

Volume Rate of Flow - Collection efficiency will vary with flow rate. It is expected that more rapid flow will enhance capture of particles larger than about 0.5 μm, at the expense of increased pressure drop across the system and at the expense of the decreased collection efficiency for particles much smaller than 0.5 μm.

Temperature - Higher temperatures will generally decrease the collection efficiency for particles larger than a few tenths microns and increase the collection efficiency for those substantially smaller. Pressure drop will increase at higher temperatures for the same flow rate in standard cubic feet per minute (scfm) or standard m^3/s.

THEORY OF OPERATION

The collector operates with the various collection mechanisms described in Section XVII. The water acts as a medium for cleaning the mesh.

The mesh is made up of about 100 layers. Each layer has a penetration which can be described by the equations

$$Pn_i = 1 - (\eta A_i/A_o)$$

or

$$Pn_i = 1 - (wA_i^*/Q)$$

where η = single target efficiency for the mesh layer;
A_i = cross-sectional area of the single mesh layer;
A_i^* = surface area of the single mesh layer;
w = migration velocity toward collection surface;

A_o = cross-sectional area of the duct or flow channel in which the layer is placed;

$Q = V_o A_o$, volume rate of flow through the layer;

V_o = face velocity of the flow through the layer.

If each layer is the same, and if collection on each layer is independent of the others, then the penetration through n such mesh layers is

$$Pn = (1 - \eta A/nA_o)^n$$

where A = total mesh cross-sectional area.

This can also be written

$$Pn = (1 - wA^*/nQ)^n$$

where A^* is total surface area.

For $n \gg 1$ and $\eta A/nA_o \ll 1$, the formula for penetration approaches the exponential equation used in Section XVII:

$$Pn \overset{o}{=} \exp(- wA^*/Q) = \exp(- \eta A/A_o).$$

For example, for $\eta A/A_o = 3$ and $n = 100$, the exponential equation gives a penetration of 0.050 and the first expression gives 0.048. Note that the single target efficiency and the effective migration velocity are related by

$$V_o \eta A = wA^* ;$$

the product of velocity, target efficiency, and cross-sectional area equals the product of the total surface area and the effective migration velocity. To predict the collection efficiency, one must calculate either η or w and know the geometry and flow rate. In the next section we will present the calculated efficiencies for the Mystaire scrubber, based partly on the MRI evaluation.

COLLECTION EFFICIENCY

The MRI evaluation centered on the collection ability of the Waterweb filter immediately downstream from the spray in the Mystaire scrubber, as simple calculations indicated very little collection of particles smaller than 3 μm occurred due to the spray itself.

MRI used formulas suitable for knitted mesh separators, assuming that the fibers in the waterweb were increased by about 5 percent by their water coating. The penetration was calculated from

$$Pn = (1 - \eta A/nA_o)^n$$

The cross-sectional area of a layer, A/n, was calculated as the product of the total length of strands in the layer, their diameter, and the fraction of strands in effective positions, taken as 0.67 from the work on wire-mesh separators by Carpenter and Othmer.[15] The product of the strand length and diameter was taken as 290 m^2/m^2 of projected area (290 ft^2/ft^2), and was increased by an assumed 5 percent due to wetting. This seems somewhat in error, because MRI indicated, "The manufacturer did supply us with a web sample and the information that every square foot of projected web area has an internal area of about 290 sq ft." The internal area would be higher than the cross-sectional area by the ratio of surface area to cross-sectional area for a cylinder, π. Thus the MRI areas are high, we believe, by a factor of π, which will be seen to make a substantial difference.

The combined single target collection efficiency was obtained from the target efficiencies due to several mechanisms by the formula (after Strauss[16]):

$$\eta_{ICD} = 1 - (1-\eta_I)(1 - \eta_C)(1-\eta_D)$$

which assumes that these mechanisms act independently; by definition:

η_I = impaction single target efficiency;

η_C = interception single target efficiency;

η_D = diffusion single target efficiency.

The impaction efficiency was obtained from an evaluation of the impaction parameter,

$$\psi = C\rho_p d_p^2 V_o/18\,\mu d_c,$$

where C = Cunningham slip correction factor (set equal to 1 by MRI);

$C = 1 + 0.17\ \mu m/d_p$ at 20°C and 1 atm pressure;

d_p = particle diameter, cm;

ρ_p = particle density, g/cm^3 (set equal to 2.8 g/cm^3 by MRI as typical of foundry)

V_o = gas velocity, cm/s, approximately the face velocity;

μ = gas viscosity, 1.8×10^{-4} poise;

d_c = diameter of collecting strand, 203×10^{-4} cm dry, 213×10^{-4} cm wet.

The impaction efficiency on a cylinder as a function of ψ was obtained from the book by Strauss.[16]

Impaction is due to the inertia of the particles, causing them to deviate from the gas streamlines flowing around the strands. Even those particles which follow the streamlines will be captured to some extent because their paths come within a particle radius of the obstacle. Such collection is said to be due to interception, and the single target efficiency of interception given by Strauss[16] and used by MRI is

$$\eta_C = (1 + R) - \frac{1}{(1 + R)}$$

where R = ratio of particle diameter to collector diameter
(strand diameter).

Brownian motion of the particles produces collection by diffusion to the strands; the rate of diffusive deposition becomes greater for smaller particles, higher temperatures and, at equal total areas of collecting surface, for collectors with smaller dimensions. MRI modified equations given by Strauss.[16] Table 8 gives the MRI results, with the final column being our recalculation of total efficiency, using the factor of π correction to take internal area to cross-sectional area.

Table 8. INDIVIDUAL AND OVERALL PARTICLE COLLECTION EFFICIENCY DUE TO IMPACTION, INTERCEPTION, AND DIFFUSION[a]

Particle size (μm)	η_I	η_C	η_D	η_{ICD}	E (%)	E (%)[b]
0.01	0	0.00004	5.8×10^{-1}	0.58	100.	100.
0.10	0	0.0010	3.1×10^{-2}	0.032	99.9	87.8
0.5	0	0.0046	8.5×10^{-3}	0.0131	93.5	57.4
1	0	0.0094	3.9×10^{-3}	0.0133	93.5	58.0
3	0.01	0.0280	2.3×10^{-3}	0.0399	99.9	92.8
5	0.10	0.0465	1.6×10^{-3}	0.1432	100.	100.
7	0.32	0.0646	1.2×10^{-3}	0.3647	100.	100.
10	0.56	0.0917	7.7×10^{-4}	0.6007	100.	100.

[a] All but last column comes from MRI report.[14]

[b] Corrected efficiency, see text.

Figure 31 shows the results of both MRI and GCA calculations of collection efficiency, graphed versus aerodynamic diameter. (The change to aerodynamic diameter produces appreciably different results only for 3 μm and 5 μm.) The effect of the factor of π is striking, suggesting that minor errors in evaluating $(1 - \eta A/A_o)$ can produce major errors in the penetration and efficiency due to the $n = 100$ power to which this is raised. We quote the MRI report on the limitations of their analysis:

Limitations of Analysis

The main limitations in the analysis are:

"1. The simple model we have used may not be applicable. However, little work has been done on wetted fibers or meshes and a suitable theory or model is not available.

"2. Assuming that the water layer does in fact increase the effective surface area of the mesh by increasing the strand diameter, the value of 5 percent, assumed by us, is strictly optional and was made only to quantify this effect.

"3. The diffusional efficiencies obtained from Ref. [16] may not be strictly applicable to our strand diameter and gas velocity. However, in the absence of other data we were left with no other choice.

"4. The presence of the water layer could favorably alter the adhesion characteristics of the mesh surface and affect the collection efficiency even more. Unfortunately, no theory has been developed for quantitatively establishing this effect even though such an effect is reported* as being very favorable towards particle collection."

---

*Davies, C.N., Air Filtration, Academic Press, New York (1973).

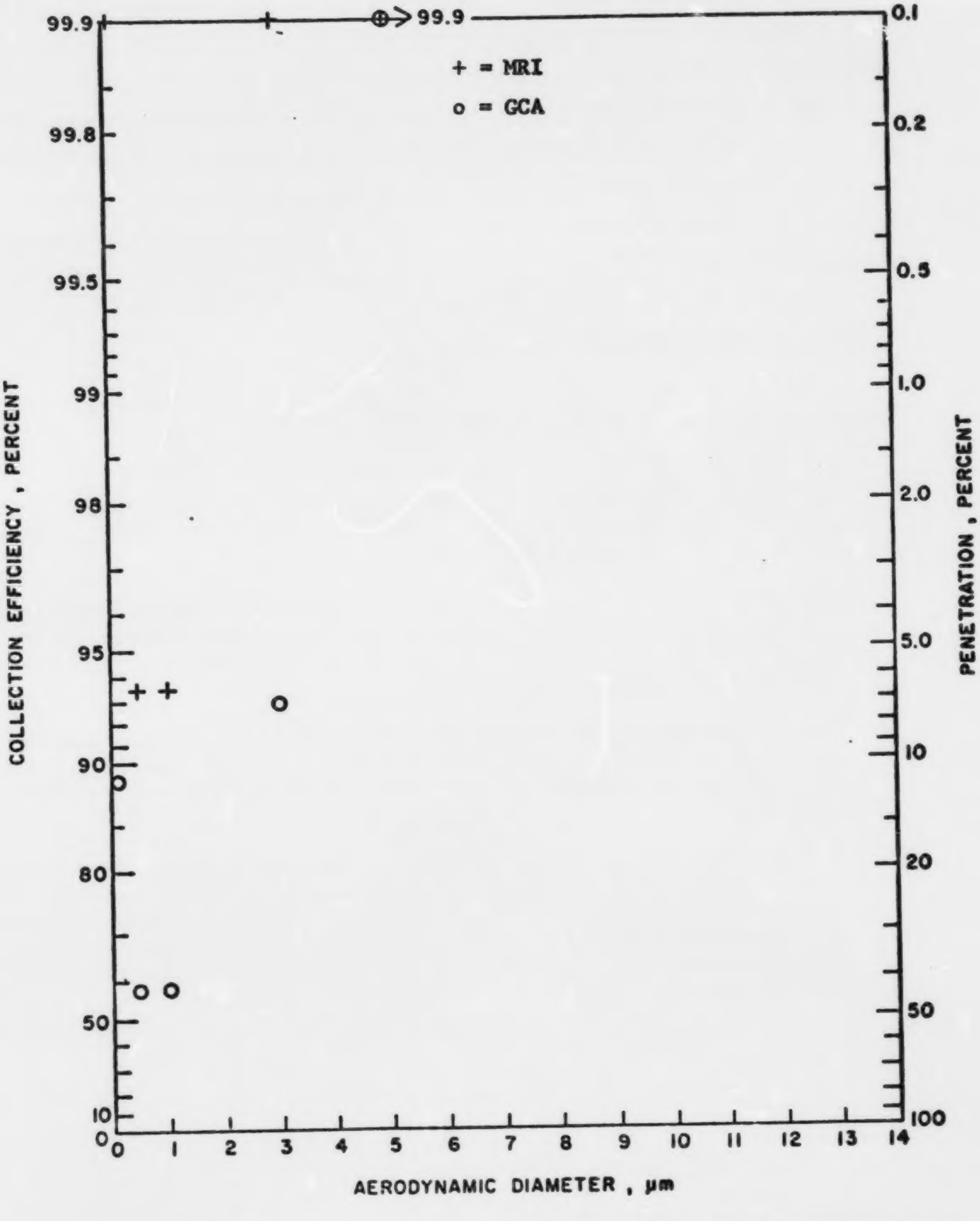


Figure 31. Estimated Mystaire collection efficiency versus particle size

POWER CONSUMPTION

The sprays will use electrical power equal to the hydraulic power (pressure times volume flow rate) divided by pump/motor efficiency (- 0.6). The spray power consumption was not indicated. The laboratory-scale device used 3 gal/min per 50 ft^3 min or 60 gpm/1000 acfm, much higher than most scrubbers use; in metric terms this would be 8×10^{-3} m^3 spray per m^3 of air.

The electrical power used by the flow through the filter web will again be the hydraulic power divided by the fan/motor efficiency. The pressure drop is about 12.5 cm WC (5"WC) which is 0.8 hp/1000 acfm or 1.27 kW per m^3/s. Electrical power would be 1.3 hp/1000 acfm or 2.1 kW per m^3/s. This is much lower than that for conventional scrubbers having similar collection efficiency.

WASTE DISPOSAL

The waste disposal problems will be quite similar to those involved for high efficiency scrubbers, and will depend upon the fraction of the rather high water rate which is involved in makeup and blowdown water (see Section XIV).

SECTION XI

PENTAPURE SCRUBBER

DESCRIPTION

A diagram of the Purity Corporation "Pentapure" scrubber is shown in Figure 32.[17] Dust-laden air mixes with water spray. The mixture accelerates in the converging section causing particle-droplet collisions and perhaps particle-particle collisions as well. The mixture is directed in a jet at the impingement surface and undergoes rapid deceleration, causing more collisions and causing the droplets, along with particles they have caught, to strike the surface, from which they run off and form a slurry. The air exhaust contains any uncaptured particulate material and droplets.

POTENTIAL APPLICATIONS

This scrubber is very similar to a venturi scrubber, thus its applicability should also be quite similar, such as foundries, refineries, paper mills, industries emitting sticky particulates, and some applications needing gas and particle removal.

Particle Characteristics

Particle Size - The 50 percent efficiency point was reached for particles with aerodynamic diameters between about 2 and 4 μm. Efficiency would be expected to increase for larger particles, decrease for smaller particles (to a minimum for particles ~ 10^{-1} μm).

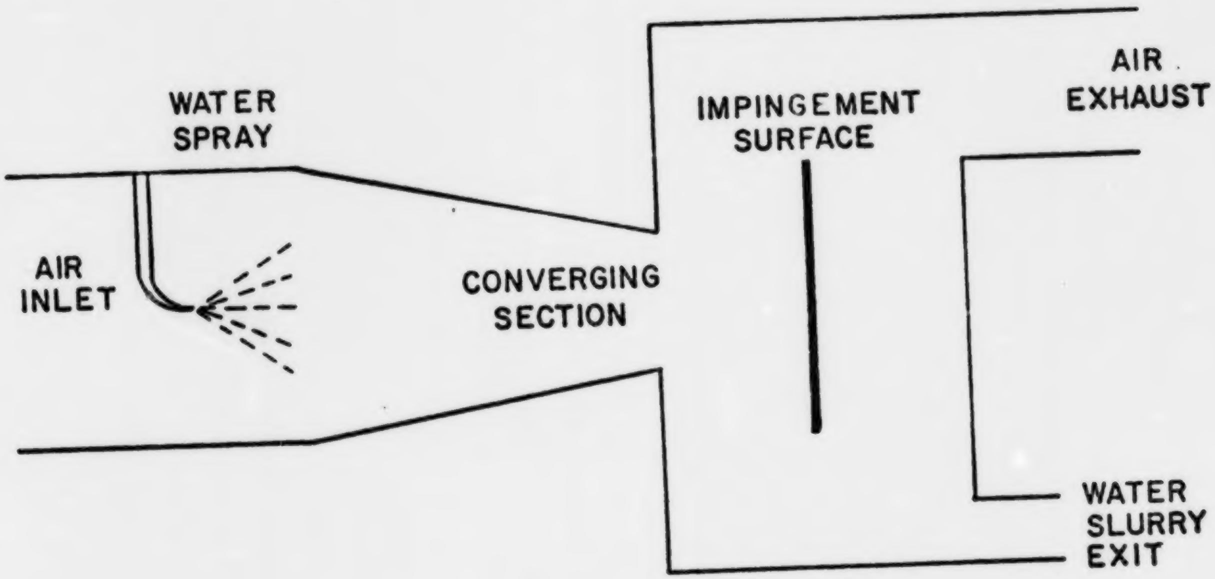

WATER SPRAY
AIR INLET
CONVERGING SECTION
IMPINGEMENT SURFACE
AIR EXHAUST
WATER SLURRY EXIT

Figure 32. Schematic diagram of Purity Corp. impingement scrubber, the Pentapure Scrubber[17]

Particle Phase - The scrubber should be suitable for either liquid or solid particulates.

Resistivity - This device should not be affected by particle resistivity.

Abrasiveness - High velocity air/particle mixtures could cause abrasion in some instances, although special materials should be able to circumvent this problem.

Corrosiveness - Again, special materials may be required in special cases.

Gas Characteristics

Gas Volume Rate of Flow - Increased velocities would improve the collection efficiency of individual spray drops, but there would be fewer drops per unit gas volume, so that the effects of volume rate of flow changes somewhat offset each other. Because the collection efficiency due to impaction is strongly dependent upon velocity differences, decreased volume flow rates will probably lead to decreased efficiencies (as well as decreased pressure drops across the scrubber, varying approximately with the square of the velocity at the throat).

Gas Temperature - The higher the temperature, the higher the gas viscosity (proportional to approximately the 0.6 power of absolute temperature), lowering collection efficiency. High temperature, unsaturated air can also produce evaporation, lowering efficiency, unless the scrubber is equipped with conditioning sprays to reduce temperature and raise humidity, as the manufacturers did at the foundry installation at which the Pentapure was tested.

Flow Velocities - Increased flow velocities should increase collection efficiency at the expense of increased pressure loss, as noted. It can be shown that the more uniform the velocity distribution in the collection zone, the higher the efficiency.

THEORY OF OPERATION

The gas flow is accelerated in the converging nozzle. Spray droplets are introduced and the spray in the gas accelerates less rapidly than the gas and particles. The particles are captured by the droplets, as described in the section on general theory, due primarily to the impaction caused by the relative motion of droplets and the air/particle mixture. The mixture is directed at the impingement surface, causing more relative motion between particles and droplets, thus more collection; some of the droplets are captured by the impingement surface as well.

COLLECTION EFFICIENCY

GCA tested the Pentapure at a gray iron foundry. The tests were designed to give the fine particulate (<3 μm diameter) collection efficiency of the scrubber section of the Pentapure installation. Figure 33 shows schematically the installation at the foundry and the location of the sampling equipment. Two kinds of efficiency determinations were made: total mass efficiency on the aerosols that entered the scrubber and mass efficiency as a function of particle aerodynamic diameter on the same aerosols, using Andersen in-stack impactors.

The EPA Method 5 minimum of 5 minutes per traverse point for the 40-point, two-diameter traverse on the inlet required 200 minutes, longer than the plant operation period, so one diameter at the inlet was done one day while one diameter was being done at the outlet. The next day, the other pair of diameters were traversed. A complete cross-section is the sum of the two one-diameter traverses.

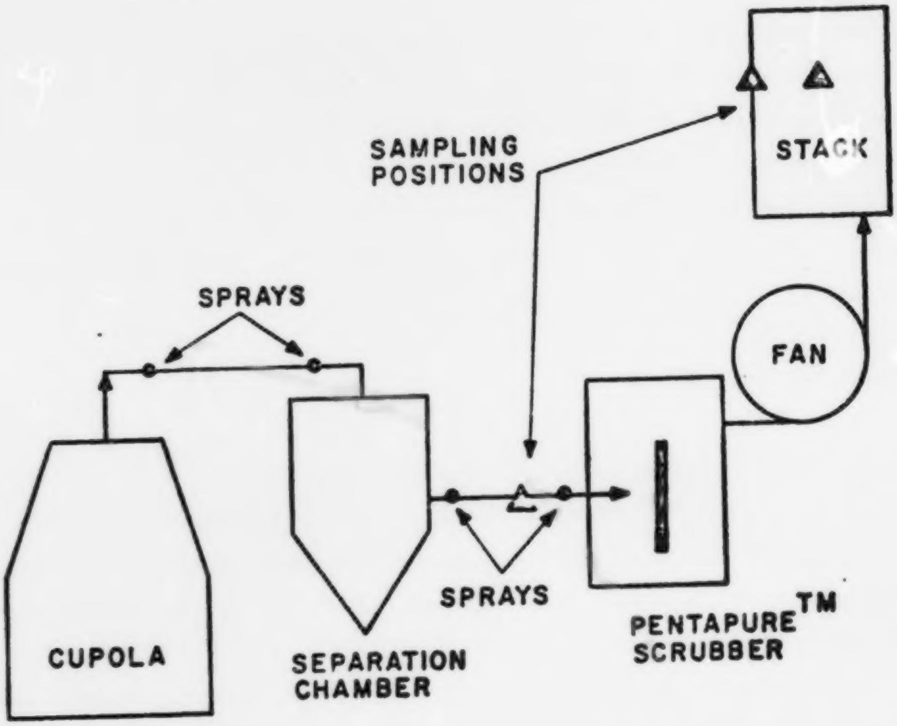

SAMPLING
POSITIONS
STACK
SPRAYS
FAN
CUPOLA
SEPARATION
CHAMBER
SPRAYS
PENTAPURE™
SCRUBBER

Figure 33. Schematic of sampling positions

The mean mass percentage efficiency was 10.0 percent. The standard deviation of this number was 2.5 percent. Thus, the efficiency of the scrubber on the rather fine aerosol which reached it after traversing the sprays and the separation chamber was:

$$E_M = (10.0 \pm 2.5)\ \%$$

The particles were primarily submicron, on a mass basis, with a mass median aerodynamic diameter at the inlet of about 0.5 μm. Such fine particles are relatively easy to sample, but they are difficult for conventional scrubbers to collect.

To measure the collection efficiency as a function of aerodynamic diameter, impactors (Andersen In-Stack Impactors) were used simultaneously upstream and downstream from the scrubber. A pre-impactor was used to remove spray droplets larger than 15 μm aerodynamic diameter and heating tapes were used to dry those remaining. The impactors were operated at 14 liters per min, $2.4 \times 10^{-4}\ m^3/s$ (0.5 cfm). Dry air flow was measured with an orifice meter and the amount of moisture collected in the condenser noted.

Figure 34 shows the particle size distribution for the inlet aerosol as the cumulative mass percentage having aerodynamic diameters as large as or larger than the values on the abscissa. The mass median diameters were 0.5 μm at the inlet and 0.4 μm at the outlet, definitely a submicronic aerosol. The fineness of the aerosol made it difficult to evaluate collection efficiencies outside the fine particle range (0 to 3 μm) because the collection stages in the finest sizing intervals would approach the maximum recommended loadings (20 mg) before much material accumulated in the larger sizing intervals. The mean collection efficiency is shown in Table 9. Graphically these results are depicted in Figure 35. The device was not an efficient collector of fine particulates, which is not an unexpected result considering the low pressure drop across the scrubbing section, an average of 6.06 in. $H_2O = 1.51 \times 10^3\ N/m^2$.

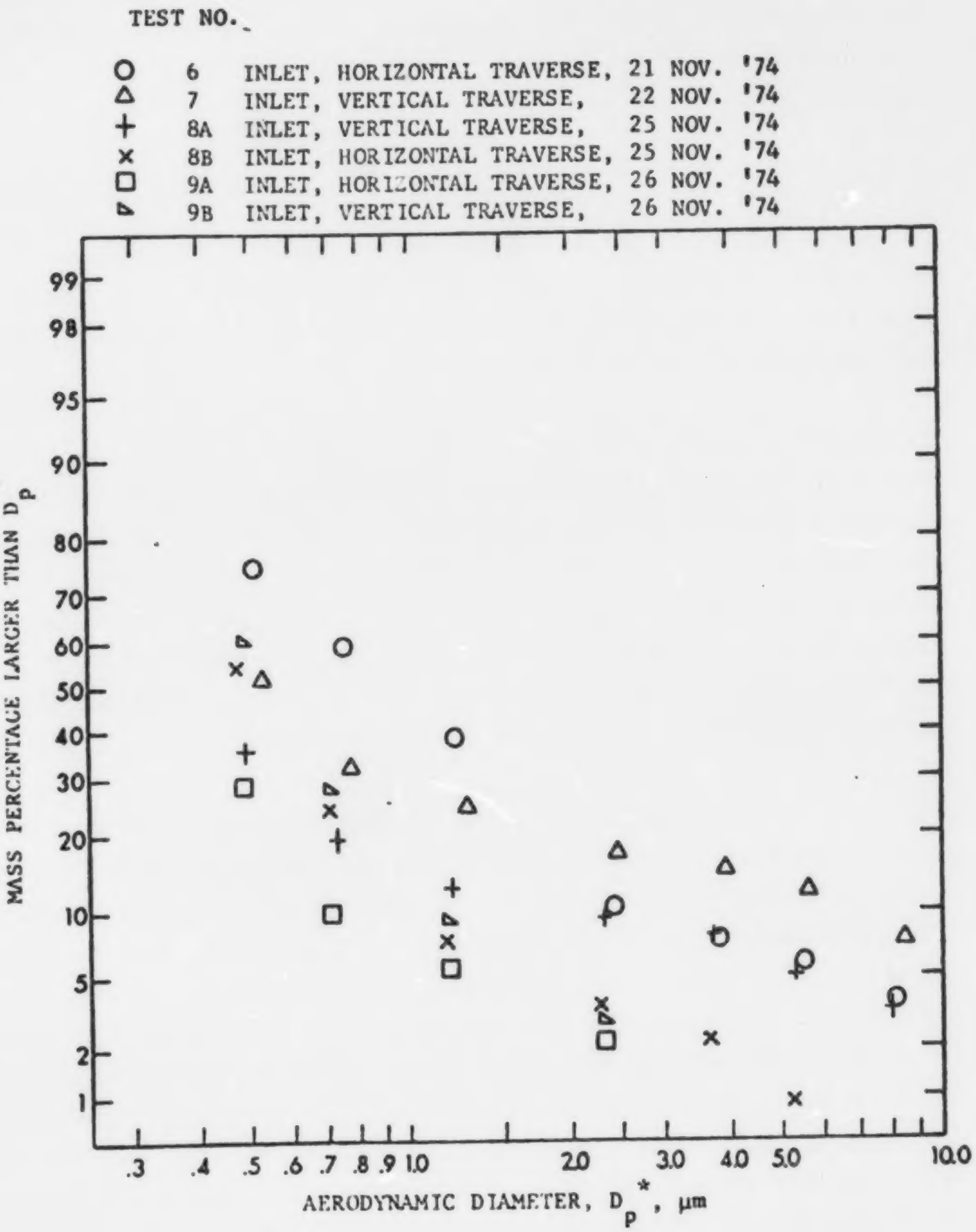


Figure 34. Inlet particle size distribution

Table 9. MEAN COLLECTION EFFICIENCY, IMPACTOR DATA

Aerodynamic diameter, μm	Mean efficiency, %
3.0	43.8
1.75	44.1
0.98	15.8
0.62	-38.5
0.25	-30.0

Possible explanations of the negative efficiencies (greater concentration of mass at the outlet in a size interval than at the inlet) include: agglomeration, deagglomeration, or other change in particle size distribution without increase or decrease in total mass; production of particles, such as by spray introduced between inlet and outlet; random data errors in the vicinity of zero efficiency; undetected systematic error.

The Scrubber Handbook gives the following formula for the penetration of a venturi scrubber:

$$Pn = \exp\left(2\, Q_L\, u_g\, \rho_L\, D_d\, F(K_p, f)/55\, Q_g\, \mu_g\right)$$

where Q_L = volume flow of scrubbing liquid, cm^3/s

u_g = gas velocity at scrubber throat, cm/s

ρ_L = scrubbing liquid density, g/cm^3

D_d = scrubbing droplet mean diameter, cm

$F(K_p, f)$ = inertial collision function

Q_g = gas volume flow, cm^3/s

μ_g = gas viscosity, poise

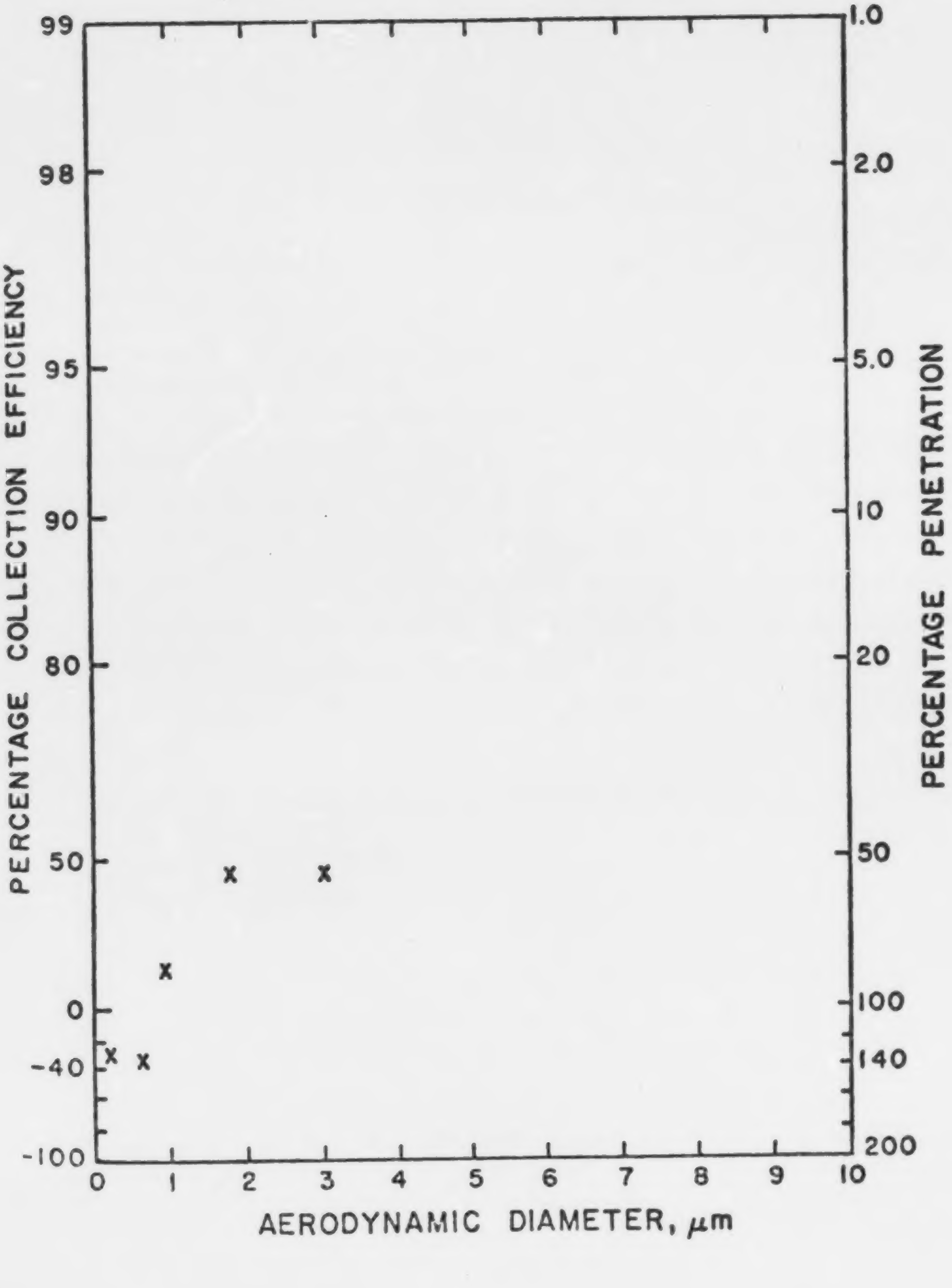


Figure 35. Collection efficiency versus aerodynamic diameter, data means for Pentapure scrubber

The function $F(K_p, f)$ depends upon a Stokes parameter, K_p, given by

$$K_p = C \rho_p u_g d_p^2 / 9 \mu_g D_d$$

where C = Cunningham correction
$C = 1 + 0.17 \times 10^{-4}$ cm/d_p
d_p = particle diameter
ρ_p = particle density.

F depends upon the parameter f, which is determined empirically and includes effects of mean gas droplet relative velocity and droplet-particle wetting. In the range where collection is appreciable ($d_p > 1$), an approximate form given in the Scrubber Handbook[8] for F is

$$F(K_p, f) = -0.156 K_p f^2.$$

The resulting expression for the penetration becomes:

$$Pn = \exp\left(- (6.3 \times 10^{-4}) f^2 Q_L u_g^2 \rho_L C \rho_p d_p^2 / Q_g \mu_g^2\right)$$

The factor f is usually between 0.25 and 0.5. Here Q_L/Q_g was $\lesssim$ 85 gal/20,000 ft^3 = 0.57×10^{-3}. The gas flow at the throat was 9.4 m^3/s (20,000 ft^3/min) through a 0.6 m (2 ft) orifice; thus, μg was 32.4×10^2 cm/s (6,400 fpm). The scrubbing liquid density was 1 g/cm^3 and the air viscosity 2.1×10^{-4} poise. For f = 0.5 and $\sqrt{C \rho_p}\ d_p = 1 \times 10^{-4}$ cm $\sqrt{g/cm^3}$:

$$Pn = \exp\left(- \frac{(6.3 \times 10^{-4})(0.5)^2(0.57 \times 10^{-3})(10.5 \times 10^6)(1 \times 10^{-4})^2}{(4.41 \times 10^{-8})}\right)$$

$$Pn = 0.808$$

Figure 36 gives the non-negative impactor data and the penetrations calculated using this formula for both f = 0.25 and f = 0.50. These calculations are approximate, partly because the scrubber geometry is somewhat different from that of the usual venturi, though not so different that their major collection mechanism differs: the impaction of particulate material on droplets, followed by the capture of the droplets.

The scrubber is not identical to a venturi scrubber, but basically both types use the acceleration and deceleration of the air to produce relative velocity gradients between the airborne particulates and the collecting droplets. The Pentapure scrubber collection efficiency is expected to be related to the pressure drop across the scrubbing section in much the same way the venturi scrubber efficiency is. The data are in agreement with theory.

The final result of a theoretical analysis performed on this type of scrubber by Midwest Research Institute[18] was that the particle size for which the efficiency would be 50 percent was 3 μm for a 2.8 g/cm^3 density particle, which corresponds to a 5 μm aerodynamic diameter (K.P. Ananth, MRI, personal communication, December 1974).

In summary, the GCA theoretical analysis and the experimental results indicated that the Pentapure scrubber collection efficiency reaches 50 percent between 2 and 4 μm aerodynamic diameter and increases for the larger particle sizes, but decreases for the smaller sizes, at least down to a few tenths microns.

POWER CONSUMPTION AND COSTS

The power used by the scrubber is predominantly the pressure drop of the air going through the scrubber (Δp) times the flow rate of the air (Q_g) in actual volume terms the hydraulic power.

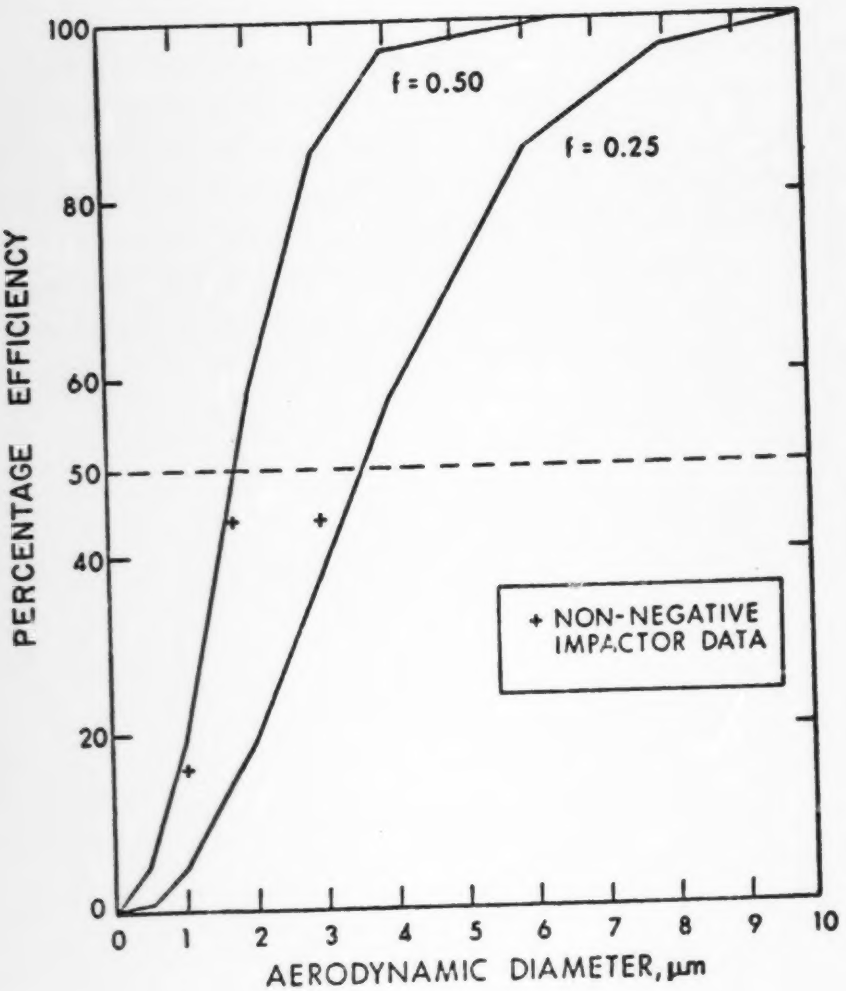


Figure 36. Data and approximate theory predictions ($f = 0.25, 0.50$; $Q_L/Q_g = 0.57 \times 10^{-3}$) for Pentapure scrubber

Flow and pressure drop were:

$$Q_g = 20 \times 10^3 \text{ ft}^3/\text{min} = 9.4 \text{ m}^3/\text{s}$$

$$\Delta P = 6.06'' \text{ H}_2\text{O} = 1.51 \times 10^3 \text{ N/m}^2$$

Thus, the air hydraulic power consumption in watts was an average 14.2 kW. A standard estimate of the electrical power necessary to achieve this air flow power is to assume combined efficiency for pumps and fans of 0.6, which would make the electrical power consumption for this operation 23.8 kW. The fan and motor combination at the site was rated at 75 hp = 5.6×10^4 W = 56 kW. The Pentapure actual power consumption, including 60 percent power efficiency, becomes 1.6 hp/1000 cfm or 2.5 kW per m^3/s.

SECTION XII

UNIVERSITY OF WASHINGTON ELECTROSTATIC DROPLET SCRUBBER

INTRODUCTION

Midwest Research Institute (MRI) used what theoretical and experimental information was available to make a preliminary evaluation of the potential applicability of the electrostatic droplet scrubber for fine particle control.

DESCRIPTION

The scrubber consists of two spray chambers, the first being countercurrent flow and the second chamber cocurrent. The scrubber is electrostatically augmented by charging of the droplets and the particulates to opposite polarities using inductive charging and corona charging, respectively. The scrubber configuration, with aerosol charging chamber, is shown schematically in Figure 37.[19] The device was developed at the University of Washington, under Dr. Michael Pilat.

POTENTIAL APPLICATIONS

The electrostatic droplet scrubber, if successfully scaled-up to industrial sized units, would have many potential applications. Any industrial source of fine particles might find the performance of the electrostatic droplet scrubber attractive. The characteristics of the particles and gas which affect the operation of the scrubber have not yet been determined, but it would seem clear that the present applications for spray scrubbers

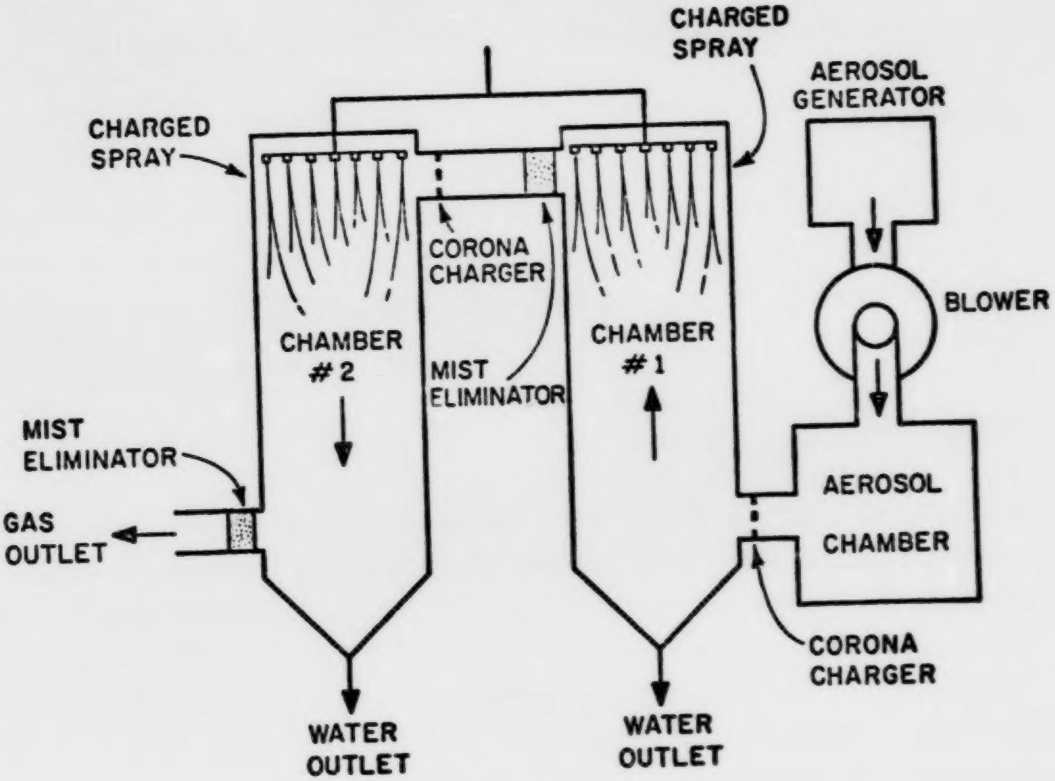

CHARGED
SPRAY
AEROSOL
GENERATOR
CHARGED
SPRAY
CORONA
CHARGER
BLOWER
CHAMBER
# 2
MIST
ELIMINATOR
CHAMBER
# 1
MIST
ELIMINATOR
AEROSOL
GAS
OUTLET
CHAMBER
CORONA
CHARGER
WATER
OUTLET
WATER
OUTLET

Figure 37. Schematic diagram of electrostatic droplet scrubber[19]

would be likely candidates for the enhanced fine particle removal capabilities of the electrostatically augmented scrubber. Some typical users of spray scrubbers are: coal-fired boilers, lead sinter crushers, phosphate rock dryers, coal dryers, electric arc furnaces, carbon black manufacturing, refineries, paper mills.

Particle Characteristics

Particle Size - The efficiency of the scrubber was reported by its developers to be greater than 95 percent for particles between 0.5 and 4 µm, with the efficiencies of greater than 85 percent for particles greater than 0.3 µm but less than 0.5 µm.

Particle Phase - Liquid particles of dioctyl phthalate (DOP) were utilized for the testing of the system. Solid particles should be equally collectible.

Resistivity - The resistivity of the particles does not affect the collection efficiency of the scrubbers without electrostatic augmentation. The resistivity of the particles may be reflected in the corona charging of the particles however, and thus may be related in a minor way to the overall collection efficiency.

Abrasiveness - The liquid DOP particles used were not abrasive; however, in an industrial application of the electrostatic droplet scrubber the abrasiveness would have to be considered due to its effect upon spray nozzles. It is not anticipated that particle abrasiveness would interfere with the overall collection efficiency of the scrubber.

Corrosiveness - Again, the liquid DOP particles used are fairly inert and would not have caused any corrosive action on the scrubber. While corrosive particles need to be considered in the choice of materials when designing a specific system, it is not expected that corrosive particles will have any effect on the overall collection efficiency of the scrubber.

Gas Characteristics

Volume Rate of Flow - The two electrostatic droplet scrubbers thus far constructed and tested by the University of Washington have had nominal capacities of 6.61×10^{-2} m^3/s (140 cfm) and 0.472 m^3/s (1000 cfm). The larger unit has been operated only at 0.33 m^3/s (700 cfm), while the smaller unit has been operated at the stated capacity. The effect of flow on collection efficiency will be discussed under "Theory of Operation."

Temperature - Collection efficiency is predicted to decrease as temperature increases, due to increased gas viscosity, for $d_p >> 0.1$ µm.

Stack Characteristics

It is conceivable that a spray scrubber could be modified to incorporate the basic elements necessary to make an electrostatic spray scrubber. The spray nozzles of an existing scrubber could be either electrified or replaced with more easily electrified spray nozzles, which would leave only the addition of a corona charging section at the scrubber inlet to approximate the electrostatic droplet scrubber.

THEORY OF OPERATION

The basic idea is to augment the collection processes usually associated with spray scrubbing (primarily impaction) with electrical collection forces as well.

As outlined in Section XVII on general theory of collection, the penetration of aerosol particles of a given size will be approximately

$$Pn = \exp(-wA/Q)$$

in which w is an effective relative velocity, A is the collection area and Q is the volume flow rate. In addition to the relative velocity produced by particle inertia and spray motion, there is an added velocity toward the droplet due to electrostatic attraction. With the particles charged to one electrical polarity and the droplets charged to the other, the primary force will be the Coulomb force:

$$F_c = q_p E$$

where F_c = electrical force, dynes

q_p = particle charge, stat-coul (3.3×10^{-10} coul)

E = electrical field, stat-volt/cm (300 volt/cm).

The electrical field at the surface of the drops will just be

$$E^* = q_d/R_d^2$$

where q_d = droplet charge, stat-coul

R_d = droplet radius, cm

and the field will decrease with the square of the distance between droplet and particle.

If the particles are exposed to the corona charging action sufficiently long to approach equilibrium charge levels, they will have a charge given approximately by,[21]

$$q_p = 3\, E_c\, d_p^2/4$$

where E_c = corona charging electric field, stat-volt/cm.

The droplet charge is more difficult to calculate, but a plausible assumption is that they have a potential, V (stat-volt), at their surface equal to that of the nozzle, which seems to have been about 5 kV,[22]

$$V = q_d/R_d.$$

The measured charge on the droplets was about 6×10^{-7} coul/g or 1.8×10^{3} stat-coul/g. Their number median diameter was about 50 μm.

The electrical contribution to the particle effective collection velocity can be estimated by calculating the electrical force and multiplying that force by the particle mobility, B. More information is available in the revie by Cooper.[23] (See Section XVII.) The University of Washington researchers, under Dr. Michael Pilat, made somewhat more elaborate calculations.

In the work reported thus far, Pilat et al.,[22] used a simple exponential (Kleinschmidt or Deutsch-type) model to estimate the difference in collection efficiency due to the addition of charge effects. This is the exp (-wA/Q) model we present above and in the section on the general theory, but w is obtained by a more sophisticated combining of impaction and electrostatic migration. Figure 38 is from the paper by Pilat et al.,[22] based in turn on the work done by Sparks,[24] in which collection efficiency was gotten from particle trajectories calculated by numerical integration of the particle equations of motion, considering diffusion, electrostatics, and particle inertia. The droplets were assumed to be 200 μm in diameter, moving at 100 cm/s, and the particles were either uncharged or carried charge equivalent to that induced by corona charging in an electric field of 1 kV/cm. This figure indicates that the minimum collection efficiency for the charged aerosol should be the maximum efficiency for the uncharged aerosol under the conditions considered. This was tested experimentally, but the measured efficiencies were much less than predicted by the simple model for both cases, especially for

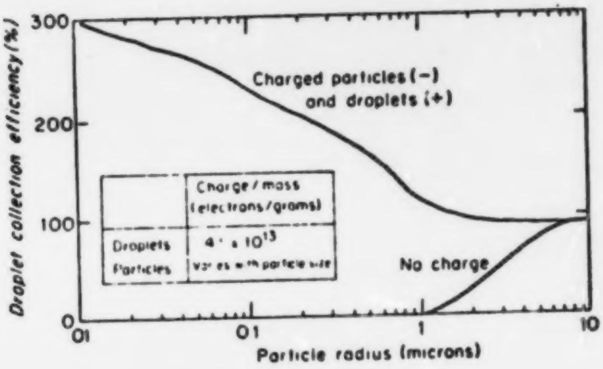


Figure 38. Calculated particle collection efficiencies for a single 200 μm diameter droplet with a 100-cm/s undisturbed fluid velocity[22]

the smaller particle sizes. The model for the charged aerosol predicts that collection efficiency should increase as particle size decreases, and exactly the opposite was measured.

COLLECTION EFFICIENCY

The mass collection efficiency of the electrostatic droplet scrubber has been determined as a function of aerodynamic particle size, utilizing simultaneous cascade impactor measurements.[22] Equipment utilized to test the two electrostatic droplet scrubbers consisted of: University of Washington Mark III Source Test Cascade Impactors, a Zeiss particle size analyzer, and a charge measuring circuit.

The fractional mass efficiency versus aerodynamic diameter was determined using simultaneously operated impactors, the results of which are given in Figure 39. Efficiency data for the scrubber operated with and without particle/droplet charging was determined to assess the effect of particle/

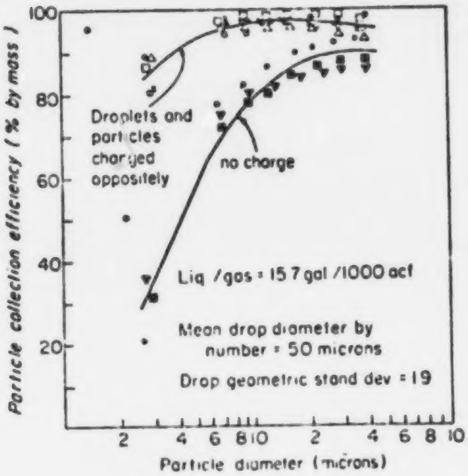


Figure 39. Particle collection efficiency of electrostatic spray droplet scrubber as function of particle size

droplet charging on collection efficiency. As previously discussed, the particle collection does not agree well with the theoretically predicted results. The theoretically derived curve for single particle collection efficiency for oppositely charged particles and droplets, Figure 38, predicts that the efficiency should decrease with increasing particle size from 0.01 - 1.0 μm and then level off (up to 10μm). The experimentally observed relationship between particle size and collection efficiency displays an increase in collection efficiency with increasing particle size from 0.3 - 1.0 μm which then approximately levels off.

The overall particle collection efficiency increased from 68.8 percent at uncharged conditions, to 93.6 percent at charged conditions, indicating a substantial improvement in collection efficiency due to the electrostatic augmentation. The collection efficiency increased from 50 percent overall to 69 percent overall by increasing the water consumption rate from 7.14 to 15.7 gallons/1000 acf, or 1 to 2 x 10^{-3} m^3/m^3, without charging. With charging, the efficiency increased from 95 percent to 98 percent for the same increase in water consumption rate.

The development of the electrostatic droplet scrubber is in its early stages, and very little data are as yet available for a more thorough analysis of the collection efficiency and the effect of other parameters.

POWER CONSUMPTION

The electrostatic droplet scrubber consumes power at four distinct portions of the equipment: fan energy to provide the pressure drop across the scrubber, the pumping energy to supply the water pressure for the spray nozzles, corona charging of the particulate, and inductive charging of the water droplets. The theoretically calculated power consumption for these are: 49 watts, 409.5 watts, 118 watts, and 22 watts respectively, per 1000 acfm (0.47 m^3/s). This adds up to a total of approximately 600 watts (0.8 hp) per 0.47 m^3/s (1000 acfm), which is much less than the predicted power consumption of conventional venturi scrubbers approximately matching the collection efficiency for fine particles.

WASTE DISPOSAL

The waste water from an electrostatic droplet scrubber would require the same treatment that would be required from any scrubber used to clean the same off-gas. Costs associated with the treatment will depend primarily on the volume of water to be treated, and the type of treatment which will be required. Present estimates are that the water consumption is approximately 2.1 liters/m^3 (15 gallons/1000 ft^3). This water consumption is higher than most scrubbers and would add significantly to the cost of water treatment if it cannot be reduced.

SECTION XIII

EFFICIENCY COMPARISON

INTRODUCTION

Each of the novel control devices has had presented with it a graph of collection efficiency as a function of particle size (aerodynamic diameter), $E(d_p)$. In this section is given a simple procedure for converting this collection efficiency curve into total mass collection efficiency for a particular control application. This allows a potential user to estimate the emissions reduction achievable by the application of the control device to his dust. The total efficiency (one minus the ratio of particulate mass outflow to particulate mass inflow) will be strongly dependent upon particle size for most control devices, thus it has to be calculated specifically for each application.

SIZE DISTRIBUTIONS

The concentration of particulate material is often presented as a function of particle size by means of the cumulative mass concentration, $M(d_p)$, which is the mass concentration of particles having diameters $\leq d_p$. More often, this is converted to a cumulative mass distribution, $G(d_p)$, by dividing $M(d_p)$ by the total mass concentration, M^*. Figure 40 is an example of such a distribution, hypothetically obtained by drawing a smooth curve through a set of data points. (This is actually a cumulative log normal distribution with a mass median, d_{p50}, of 1 μm and a geometric standard deviation, σ_g, of 2.)

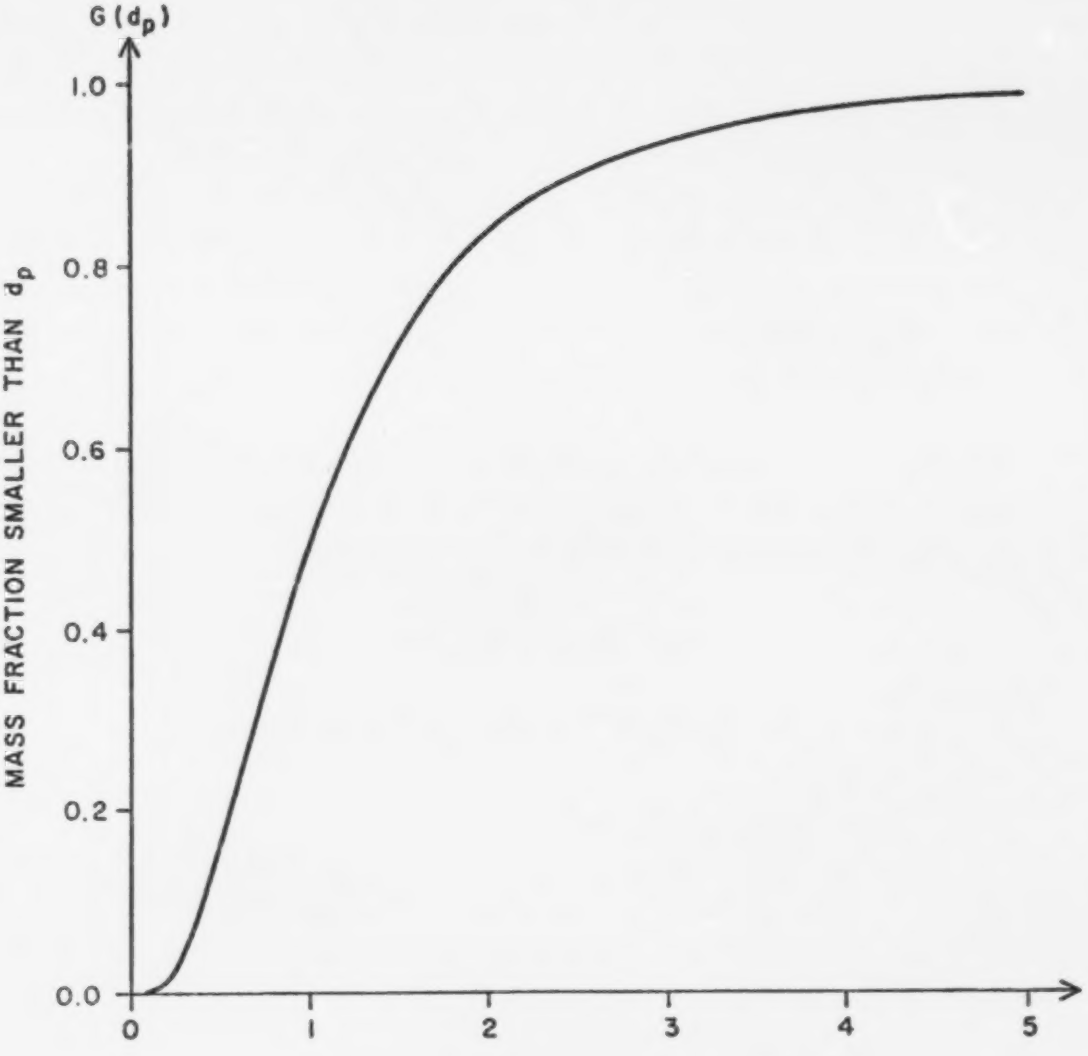


Figure 40. Hypothetical cumulative mass distribution (log normal, median = 1, geometric standard deviation = 2)

In order to estimate collection efficiency for a particular process and control device, we must know the size distribution at least approximately. Often it is obtained from cascade impactor measurements.

CONTROL DEVICE EFFICIENCY VERSUS PARTICLE SIZE

Figure 41 is a hypothetical collection efficiency curve, such as those presented here for novel control devices. It shows collection efficiency $E(d_p)$ as a function of particle diameter, d_p.

The essence of the method presented here is: obtain average efficiencies for each of a number of size intervals; multiply these average efficiencies, size-interval-by size-interval, by the mass fractions contained within the intervals; sum these products.

Let $G(d_p)$ be the fraction of the mass concentration contained in particles $\leq d_p$ in size. This is the cumulative mass distribution, an example of which is shown in Figure 40, and which is defined as

$$G(d_p) = M(d_p)/M^*.$$

The total mass collection efficiency E_M is given by

$$E_M = (1/M^*) \int_o^{M^*} E(d_p)\ dM$$

which is the same as

$$E_M = \int_o^1 E(d_p)\ dG$$

To evaluate this, divide the collection efficiency curve into enough segments so that each segment seems approximately a straight line.

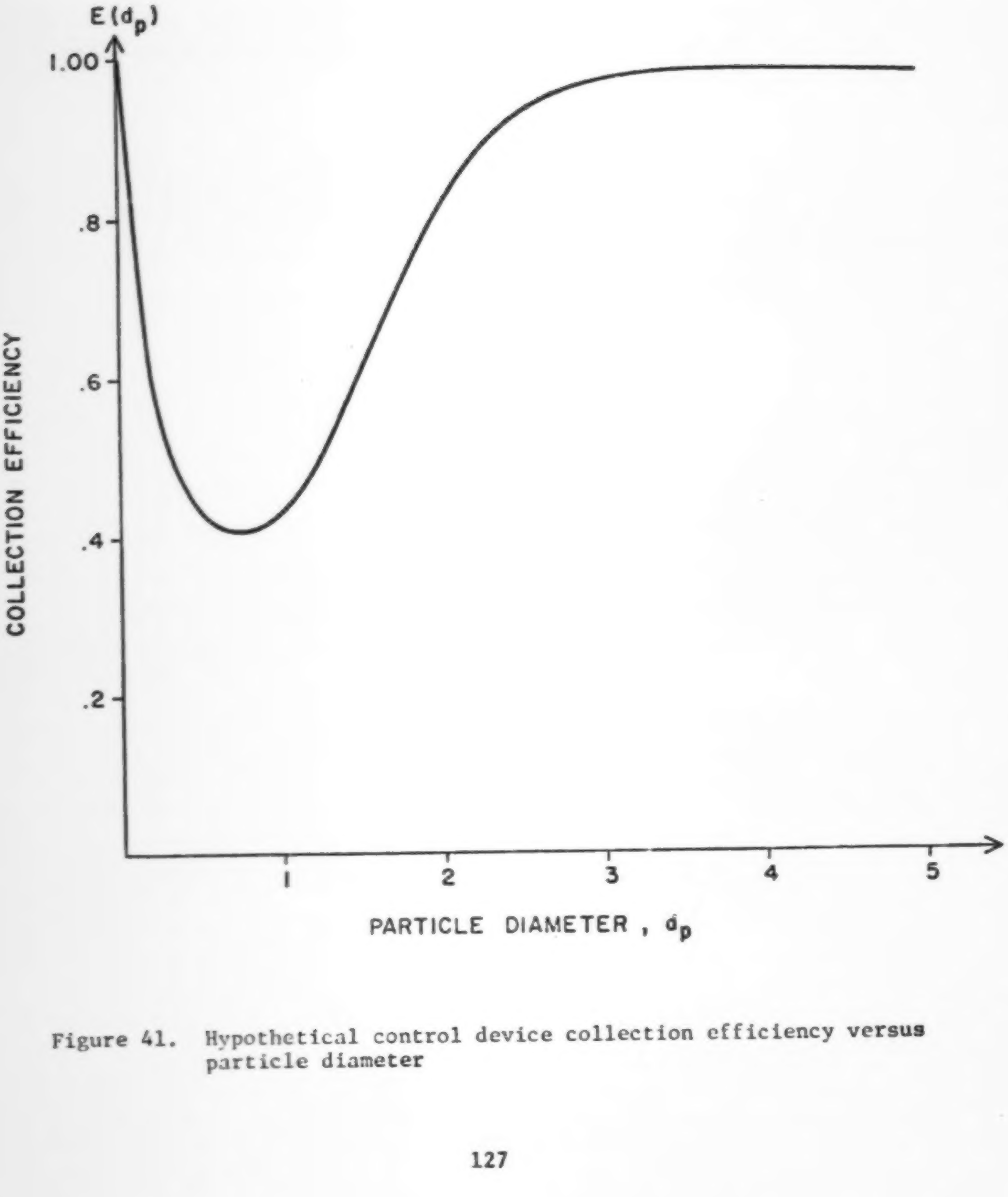


Figure 41. Hypothetical control device collection efficiency versus particle diameter

The size intervals do not have to be all the same width; make them narrower where the efficiency is more curved, wider where it is nearly straight. The intervals must be the same for the efficiency curve and the size distribution curve, however. The d_p values which are the interval demarkations are d_{pi}. The fraction of the mass in the interval from d_{pi} to d_{pi+1} is just the difference between the cumulative mass distribution values at these two diameters, $G_{i+1} - G_i$. The efficiency value to use on this interval is just the efficiency at the mid-point, $E_{mi} = E\ (d_{pmi})$, where

$$d_{pmi} = \left(d_{pi+1} + d_{pi}\right)/2.$$

Then the mass efficiency can be obtained from summing the products of the mid-point efficiency and the fraction of mass on the intervals:

$$E_M \doteq \sum_{i=1}^{N} E_{mi}\left[G_{i+1} - G_i\right]$$

The error in such a technique can be estimated by cutting the intervals in half (using twice as many intervals) and repeating the process; the difference between the two estimates will normally be larger than the difference between the second trial solution and the true solution.

As an example, we will compute the efficiency for the hypothetical distribution and the hypothetical control device efficiency given in Figures 40 and 41. This is done in Table 10. The total mass efficiency is

$$E_M = 0.220 + 0.211 + 0.092 + 0.035 + 0.15 = 0.573$$

$$E_M = 57.3\%$$

Table 10. EXAMPLE OF CALCULATION OF PREDICTED MASS COLLECTION EFFICIENCY

Size interval, i	Interval end point		Mid-point d_{pmi} (μm)	Mid-point efficiency $E(d_{pmi})$	Cumulative distribution		Mass fraction in interval $G_{i+1}-G_i$	$E(d_{pmi})$ $\times(G_{i+1}-G_i)$
	d_{pi} (μm)	d_{pi+1} (μm)			G_i	G_{i+1}		
1	0	1	0.5	0.44	0.0	0.5	0.5	0.220
2	1	2	1.5	0.62	0.5	0.84	0.34	0.211
3	2	3	2.5	0.92	0.84	0.94	0.10	0.092
4	3	4	3.5	1.00	0.94	0.975	0.035	0.035
5	4	5	4.5	1.00	0.975	0.99	0.015	0.015
								0.573

This is the efficiency we would expect for the control device operating on the specific aerosol. (Intuitively, we would expect approximately this result; most of the aerosol is between 0 and 2 μm and the efficiency curve seems to average about 60 percent in this range.)

To summarize the procedure:

a. Segment the curves for efficiency and cumulative particle mass size distribution, using particle size intervals which are close enough that the curves are nearly straight lines between the particle sizes chosen.

b. Obtain mid-point values for efficiency.

c. Calculate the product of the mid-point efficiency $E\ (J_{pmi})$ and mass fraction on each interval $(G_i + 1 - G_i)$.

d. Sum these products.

e. The mass efficiency for the control device on this aerosol is the result.

f. To estimate the error, redo the calculation with half as many intervals. The difference is approximately the error.

In mathematical terms, to obtain the total mass efficiency, we have numerically integrated the product of efficiency and fractional mass concentration. We estimate the error by the rate of convergence as the intervals are made smaller.

If only fine particle ($d_p \leq 3$ μm) efficiency is desired, form $G(d_p)$ from $M(d_p)$ using $M^* = M(3\ \mu m)$ and repeat the process above with an upper size limit at $d_p = 3$ μm.

CUT DIAMETER COMPARISONS

Calvert[4] compared several different scrubbers on the basis of their cut diameters, the particle diameter at which their efficiencies are 50 percent. This has the following advantages:

1. A single number is obtained for comparing collection efficiency curves of different devices, quite useful if the dominant collection mechanisms are the same.

2. If the curves are similar in shape, then this number is quite informative about relative efficiencies for particle collection, and for certain particle size distributions, the efficiency can be predicted.

It has the following disadvantages:

3. If the curve has a minimum or a maximum within the range, there may be two particle sizes at which the efficiency is 50 percent.

4. Some devices may be so efficient that there is no particle size for which the collection efficiency is 50 percent.

5. If the collection efficiency versus particle size curves of the two devices being compared have quite different shapes, then the use of the cut diameter may be very misleading with regard to their overall efficiency on particular aerosols.

6. Choice of diameter (aerodynamic, geometric, mobility, etc.) is a problem. For those novel collection devices evaluated here for which such a treatment seemed sensible, we have listed in Table 11 the aerodynamic cut diameters.

Table 11: AERODYNAMIC CUT DIAMETERS FOR SEVERAL NOVEL CONTROL DEVICES

Control device	Aerodynamic cut diameter[a]
Aronetics	0.3 μm
Braxton with cyclone or scrubber	2.0
Centrifield	0.65
CHEAF	-
Dynactor	0.55
Lone Star	-
Mystaire	-
Pentapure	3.0
University of Washington	-

[a] See Appendix for definition of aerodynamic diameter. This is the largest aerodynamic diameter for which the control device has an efficiency of 50 percent.

AVERAGE FINE PARTICLE EFFICIENCY

Another method will now be presented for obtaining a single efficiency number with which to compare control devices. Recently, interest has focused on the fine particle range, particles with diameters less than or on the order of 3 μm, because these particles persist in the atmosphere longer than larger particles, generally, and they tend to escape the human body's respiratory defenses. (See Lippman's[25] and also see Friedlander's[26] articles for example, for more details.) The average fine particle efficiency for a control device in the range 0 to 3 μm would just be

$$E_f = (3\ \mu m)^{-1} \int_0^{3\mu m} E(d_p)\ d(d_p),$$

the integral of the efficiency curve from 0 to 3 μm divided by 3 μm. This weights all particle sizes equally in the range 0 to 3 μm.

It has the following advantages:

1. A single number is obtained for comparing the collection efficiency of different devices.
2. If the collection efficiency curves are similar, or not, this number is quite informative about relative efficiencies.
3. The number obtained is a kind of efficiency rather than a particle diameter.
4. The number is unambiguous, whether or not the efficiency curve has a maximum or minimum in the range, whether or not efficiency of 50 percent occurs in the range.
5. Regardless of collection efficiency curve, the number will be informative, though not definitive, about fine particle collection efficiency.

It has the same disadvantage as the cut diameter concept:

6. Choice of diameter for the collection efficiency curve is still problematic. (But we shall use aerodynamic diameter, as does the cut diameter method.)

To calculate the average fine particle efficiency by detailed integration would be tedious, and often not warranted by the accuracy of the data, so we use the following numerical method for its calculation:

a. Subdivide the collection efficiency curve from 0 to 3 μm into six equal sub-intervals, 1/2 μm wide.
b. Evaluate the efficiency at the mid-points of these sub-intervals (0.25 μm, 0.75 μm, 1.25 μm, 1.75 μm, 2.25 μm and 2.75 μm).
c. Add these six efficiency values and divide by six.
d. The result is the approximate average fine particle efficiency.

Parenthetically, we add that the method is just the mid-point quadrature evaluation of the integral, and the absolute error can be shown to be less than 1/24th the maximum absolute value of the curvature (second derivative with respect to particle size) of the efficiency curve times $(1/2\ \mu m)^2$ or $0.25\ \mu m^2$. See a numerical analysis text for more information.

In Table 12, we list the average fine particle efficiencies for the novel control devices as determined from this method and the curves given in the sections on the devices themselves. (The true fine particle efficiencies will, of course, depend upon the aerosol to be controlled, just as is true with the cut diameter estimates.)

Table 12. AVERAGE FINE PARTICLE EFFICIENCIES FOR THE NOVEL CONTROL DEVICES

Control device	Average fine particle efficiency
Aronetics	97.4
Braxton with cyclone	47.3[a]
Centrifield	72.3[a]
CHEAF	95.2[a]
Dynactor	79.2[a]
Lone Star	99.89
Mystaire	76.3[b] 97.8[c]
Pentapure	29.0[a]
University of Washington	94.5[a]

[a] Includes extrapolated values

[b] GCA calculations

[c] MRI calculations

SUMMARY

The total mass efficiency can be calculated for the novel control devices for aerosols other than those on which they were tested by using the methods of this section, thus facilitating a choice as to which might be applicable to one's specific process. Two methods are presented for comparing control device efficiencies without knowing the particle size distribution. The average fine particle efficiency number appears superior to the particle cut diameter approach.

SECTION XIV

COST COMPARISON

INTRODUCTION

The goal of this section is to indicate how cost comparisons can be made for various particulate control options, including the novel control devices discussed in this document. The approach is based upon that developed by Edmisten and Bunyard[27] while employed by EPA's predecessor, the National Air Pollution Control Administration. In brief, the goal is to develop a single cost parameter, the total annualized cost, by which different air pollution control devices can be rationally compared with respect to cost. This is quite useful because, for example, electrostatic precipitators have relatively high initial costs and relatively low operating costs in comparison to scrubbers of comparable collection efficiency.

Edmisten and Bunyard[27] divided the costs into three categories:

- Capital investment cost - This includes the control hardware cost, the cost of auxiliary equipment and the cost of installation, including initial studies.
- Maintenance and operating costs - These are taken on a yearly basis, averaged over the life of the equipment.
- Capital charges - These are what it costs to borrow the money equivalent to the capital investment, usually 6 to 12 percent per year, plus taxes and insurance.

ANNUALIZATION OF COSTS

To convert these various costs into a single number, the total annualized cost, one sums the annual capital investment depreciation, the operating and maintenance costs, and the capital charges (CC).

The usual method of depreciation in such contexts is to assume straight-line depreciation. One estimates the life of the equipment, Edminsten and Bunyard[27] suggested 15 years, and figures the yearly depreciation as the capital investment divided by the life expectancy. Thus, the total annualized cost (TAC, \$/yr) is given by

$$TAC = CI/L + MO + CC$$

where

CI = capital investment, \$
L = lifetime, yr
MO = yearly maintenance and operating costs, \$/yr

Generally MO and CC will be nearly proportional to CI.

For more details on conventional control device costs, see the article by Edmisten and Bunyard.[27] The literature on filters, scrubbers, and electrostatic precipitators often will provide additional information:

- For scrubbers, see also the articles by Hanf and MacDonald,[28] by Fraser and Eaton,[29] and the Scrubber Handbook by Calvert *et al*.[8]
- For fabric filters, see also the article by Fraser and Foley[30] and the report by McKenna.[31]
- For electrostatic precipitators, see also the articles by Schneider *et al*,[32] and by Benson and Corn.[33]

POWER COSTS

Although much of the necessary information on costs will have to be obtained from the manufacturers for a specific application, one can estimate power costs from the information in this document.

Generally the power consumption figures are given in terms of kW per m^3/s flow rate or hp per 1000 acfm flow rate. (Note: 1 hp = 0.746 kW, 1000 acfm = 0.47 m^3/s.) Where the power is given as hydraulic power (pressure drop times volume flow rate) a pump/fan/motor efficiency factor must be used (as a divisor) to convert to actual electrical power; this efficiency factor is generally about 0.6, whether fans are moving gas or pumps are moving liquid. The power cost (PC, \$/yr) is given by:

$$PC = Q \times (P/Q) \times CP \times TT$$

where

Q = volume flow rate, m^3/s
P/Q = power consumption per unit flow rate, $kW/(m^3/s)$
CP = cost of power, \$/kW-hr
TT = total yearly operating time, hr.

Certain forms of power may be nearly free: the recovery of waste heat is free with regard to operating costs, although it will add to the capital investment and thus to the costs associated with capital investment.

As with other costs, the power costs will vary considerably from situation to situation. The P/Q information presented for the novel devices should aid in the estimation of these costs.

Using the methods of this section, a single cost parameter can be developed by which to compare control system alternatives. This parameter is the total annualized cost.

Although specific circumstances will also greatly affect waste disposal costs, we present a brief discussion of these costs to highlight that having captured the airborne material is not the final stage in air pollution control. Generally, that final phase is to convert the captured material into a solid for such uses as landfill or to find a method for recycling some or all of the captured material. The scrubbers will produce waste water which must be handled properly; dry collectors and wastewater treatment will produce solid wastes which must be used or disposed.

WASTE WATER

A cost incurred by wet scrubbing which estimates should take into account is the cost of cleaning the waste water generated by this type of device. Depending on the type of contaminant and the degree of treatment necessary before discharge, the cost can vary an order of magnitude. It can be more expensive than the raw water cost.

If scrubber waste water is not discharged to a municipal sewer, it must be brought up to sufficient quality so that it can be discharged to a receiving body, or disposed of in some manner such as lagooning or deep-well disposal. The quality to which the water must be brought for discharge to receiving bodies such as streams, lakes, estuaries, coastal and marine waters, etc., depends in general on the uses (such as swimming, recreational boating, fish and wildlife, etc.) designated for the receiving body. Such information may be obtained from the state agency responsible for water quality standards or water pollution control. In many instances, scrubber waste water will be processed through the plant wastewater treatment facility.

So that proper treatment may be specified, it is necessary to characterize the effluent from the scrubber. Figure 42 diagrams treatment processes for various degrees of contaminant removal.[34] For discharge to municipal sewers or to the plant treatment facility, discharged waste water must not disrupt such processes as biological oxidation, or overload such processes as carbon filtration, or ion exchange. Acids and alkalies must be neutralized before biological oxidation. Toxic materials such as cyanides, metallic ions, barium chloride, chromic acid, aldehydes, germicides, dye stuffs, radioactive isotopes, etc., have rigid discharge standards and must be treated appropriately. Phenols, which result in tastes and odors in water and are rigidly controlled, are often encountered in waste water from foundry scrubbers because coke and core binders contain phenols. Shock discharges (such as emptying a recirculation reservoir for a scrubber) should be equalized so that trickling filters, sludge basins, etc. downstream are not flushed with the resultant discharge of raw effluent to the receiving body. Thermal discharges, perhaps from scrubbers used to cool as well as clean effluent gas, reduce dissolved oxygen and may kill sensitive species in receiving bodies. Thermal discharges can be controlled by ponding, spray systems, or cooling towers. In certain applications, cleaning scrubber waste water may result in product recovery where expensive solvents are condensed or valuable materials enter effluent gas.

Costs may be estimated from Figure 43 after the degree of treatment has been determined.[35] The cost, plotted on the ordinate of Figure 43 should be multiplied by a factor for the increase in the Marshall and Stevens Equipment Cost Index (found in Chemical Engineering) from 1970 (M & S = 303.3) to the present (M & S = 444). When planning a scrubber installation, the plant engineer responsible for wastewater treatment

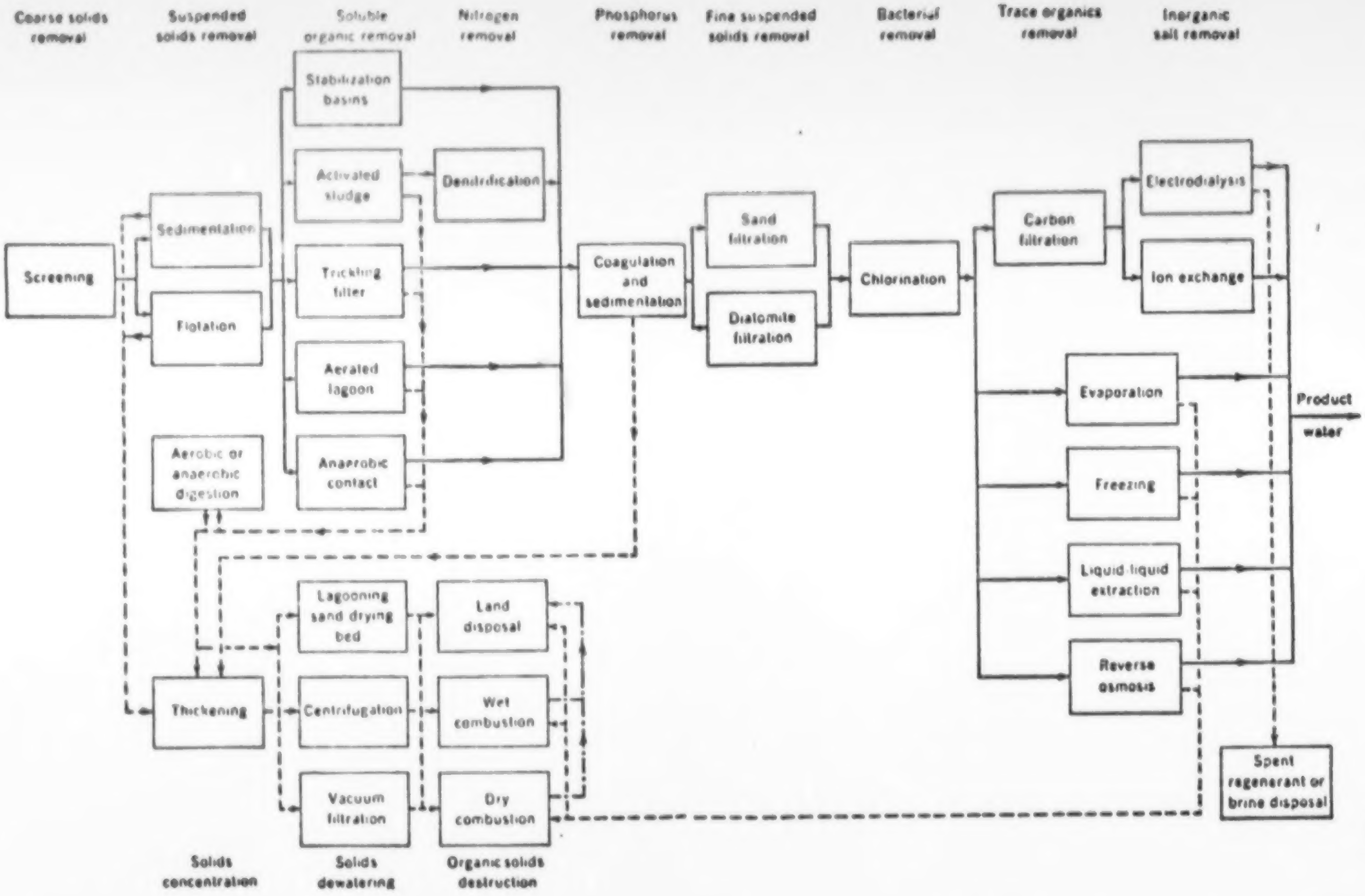

Coarse solids removal
Suspended solids removal
Soluble organic removal
Nitrogen removal
Phosphorus removal
Fine suspended solids removal
Bacterial removal
Trace organics removal
Inorganic salt removal
Screening
Sedimentation
Flotation
Aerobic or anaerobic digestion
Stabilization basins
Activated sludge
Trickling filter
Aerated lagoon
Anaerobic contact
Denitrification
Coagulation and sedimentation
Sand filtration
Diatomite filtration
Chlorination
Carbon filtration
Electrodialysis
Ion exchange
Evaporation
Freezing
Liquid-liquid extraction
Reverse osmosis
Product water
Spent regenerant or brine disposal
Thickening
Lagooning sand drying bed
Centrifugation
Vacuum filtration
Land disposal
Wet combustion
Dry combustion
Solids concentration
Solids dewatering
Organic solids destruction

Figure 42. Treatment of waste waters to effect various degrees of contaminant removal[34]

Reproduced from best available copy.

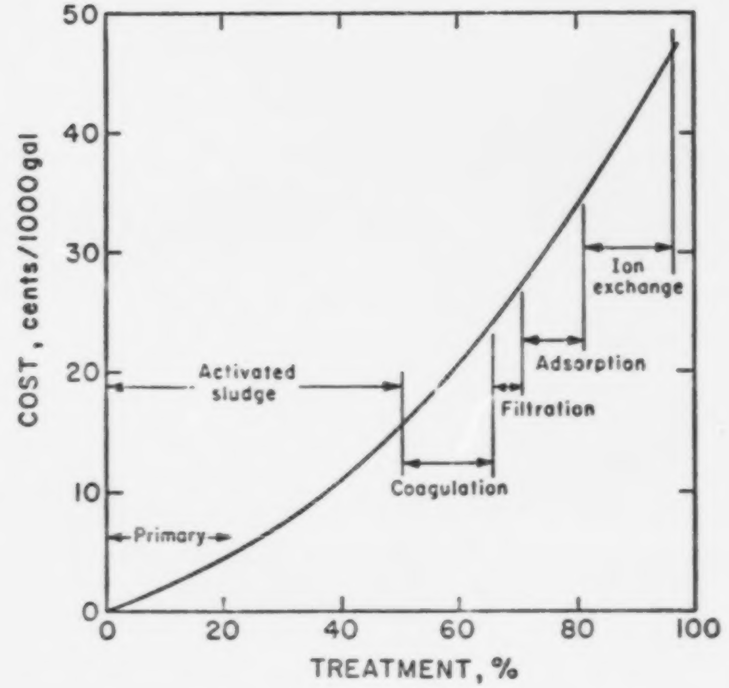


Figure 43. Relationship between total water cost and treatment[35]

should be consulted and outside technical help sought if necessary. For more information about wastewater treatment, consult a text such as that by Eckenfelder, Industrial Water Pollution Control.[34]

SOLID WASTES

Just as disposal of waste water from scrubbers results in a cost to the user, so does disposal of solid wastes from dry collectors, such as cyclone precipitators, baghouses, wall filters, rotary drum filters, etc., result in some expense.

Solid waste disposal cost can be broken down into costs of hauling and costs of disposal. Hauling costs are dependent on the type of equipment, length of hauls, type of route and traffic encountered, and the number of employees necessary. Figure 44 shows how this type of calculation was made, for residential collections.[36] The data are intended for the purpose of demonstrating the method, but appear acceptable for rough estimates. Costs of disposal usually means the cost of a sanitary landfill, although other disposal methods such as ocean dumping or mine refilling are possible. Components of sanitary landfill cost are cost of site, degree of compaction, and cost of developing such things as access roads, water supply, fences, landscaping, water runoff diversion facilities, etc. Experience shows a cost of $2.00 to $7.00/ton of refuse handled. In many instances, a particular industrial facility will contract to have solid wastes removed. It is hoped that the above comments will be helpful in determining price.

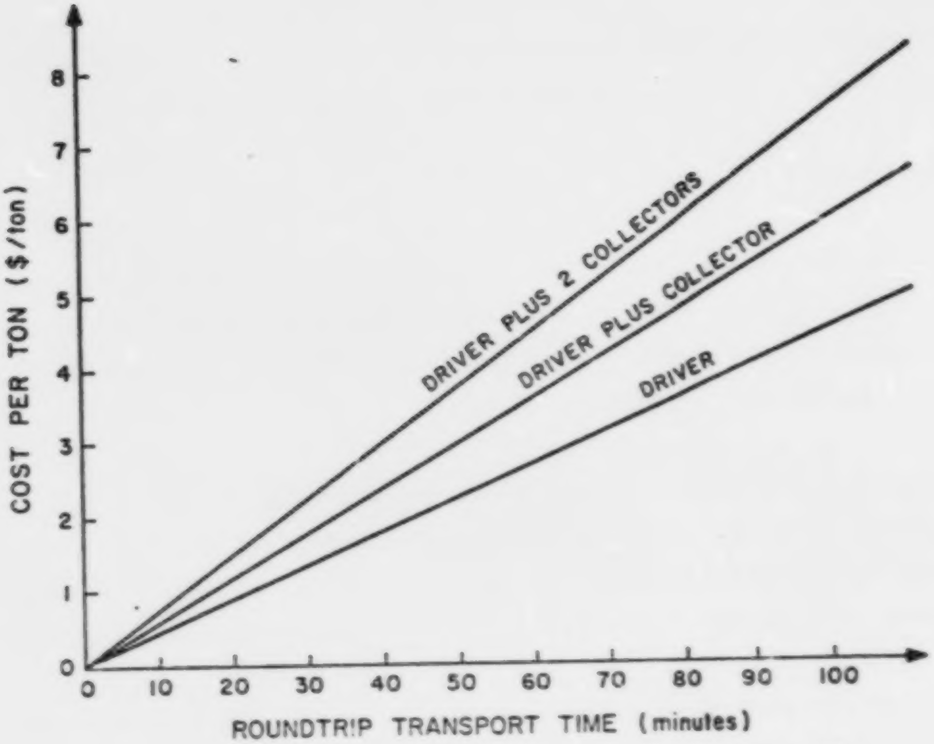


Figure 44. Collection vehicle hauling costs[36]

The following data was used to derive the graph above:

	direct haul
(1) time-based transportation costs, yearly	
• vehicle amortization	$ 5260
• driver's salary and fringe benefits	10625
• collector's salary and fringe benefits	9375
• vehicle insurance, licenses, taxes	1500
	26760
total time-based transportation cost per minute	$0.214
(2) mileage-based transportation costs	
• fuel, oil, tires cost per mile	0.080
• maintenance and repair cost per mile	0.050
total mileage-based transportation cost per mile	0.130

SECTION XV

POWER COMPARISON

Most of the novel control devices tested used power in pumping scrubbing liquid or in moving the gas or both. The Aronetics and the Lone Star scrubbers derived power from waste heat, which in some sense is "free" and should not be treated in the same manner as purchased power. The major parameters by which control systems can be compared are their collection efficiencies as functions of particle size and their total annualized costs. A significant factor in the latter is power consumption. Moreover, the nation is becoming more conscious of the need to conserve energy. For these reasons we have presented in this brief section Table 13 which contains a summary of the power requirements of the control devices evaluated. The first column lists the devices. The next four columns have power consumption per 1000 acfm of gas treated, separated into blower power, pump power, other power, and total power consumption. (To obtain the metric equivalents, $kW/m^3/s$, multiply hp/1000 cfm values by 1.58.)

Figure 45 contains theoretical/empirical lines presented by Calvert[4] for various scrubber types. The aerodynamic cut diameter is graphed against various measures of power consumption (hydraulic power per volume flow rate). (There is a bit of a difference between Calvert's aerodynamic cut diameter definition and the standard definition. This difference has been neglected in the drawing of the curves and the addition of the data from the novel device evaluations. (See Appendix.) Point A is for the Aronetics scrubber if the waste heat is free and not counted as power consumed. Point B is for the Braxton device used with a low energy

Table 13. POWER CONSUMPTION FIGURES FOR NOVEL CONTROL DEVICES EVALUATED FOR IERL-RTP

Control system	Power consumption,[a] hp/1000 acfm			
	Air blower(s)[b]	Water pump(s)[b]	Other	Total
Aronetics Two-Phase Scrubber	0.0	2.4	400[c]	26. 2.4[d]
Braxton Sonic Agglomerator	0.5	f	0.38	0.9
	5.3[e]	f	0.38	5.7[e]
	0.83[g]	f	0.38	1.2[g]
Centrifield Scrubber	2.8	f	0.0	2.8
Cleanable High Efficiency Air Filter	5.5	f	0.0	5.5
Dynactor Scrubber	0.0	3.3	0.0	3.3
Lone Star Steel Steam-Hydro Scrubber	0.0	f	200-300[c]	200-300 0.0[d]
Mystaire	1.3	f	0.0	1.3
Pentapure Scrubber	1.6	f	0.0	1.6
U. of W. Electro-Static Spray Scrubber				~ 0.5

[a] $1.58 \text{ kW}/(\text{m}^3/\text{s}) = 1.58 \text{ kJ}/\text{m}^3 = 1.00$ hp/1000 cfm.

[b] Blower or pump plus motor assumed to have 60 percent overall power efficiency.

[c] Waste heat.

[d] Omitting waste heat consumption.

[e] Including very high-efficiency cyclone, $\Delta p = 30'' H_2O = 75$ cm WC.

[f] Unspecified, assumed negligible.

[g] Including low-energy scrubber, $\Delta p = 3$ cm WC.

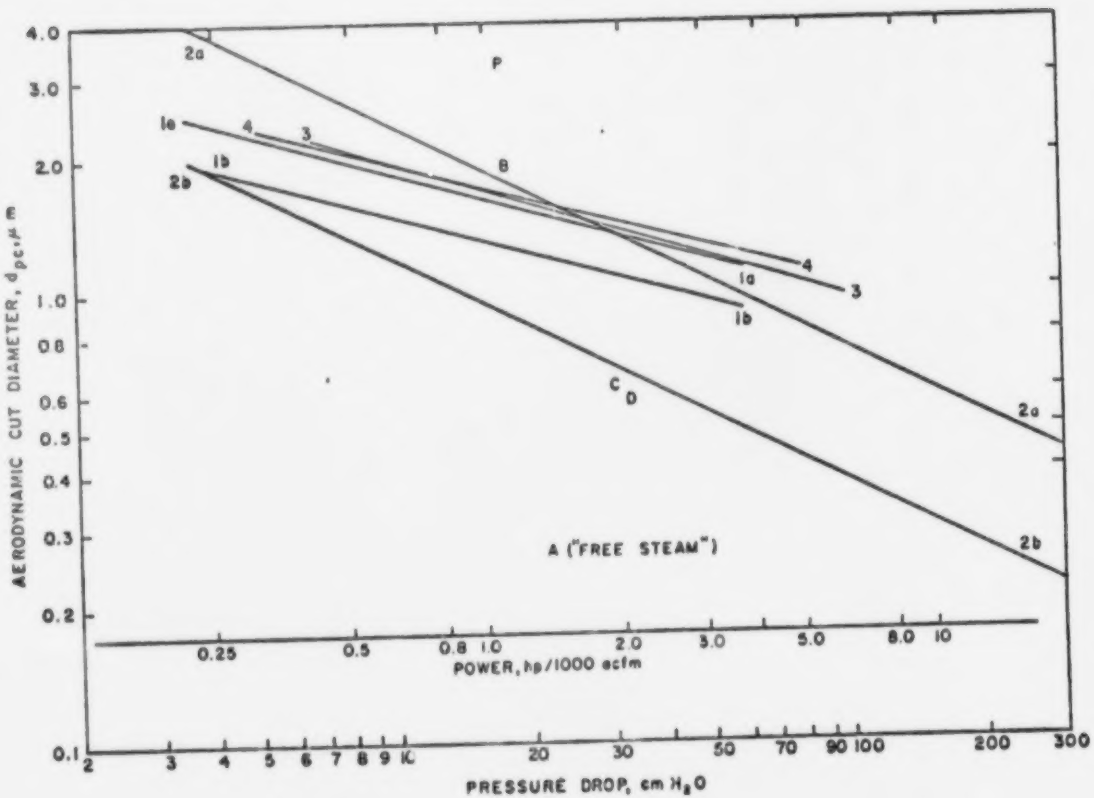


Figure 45. Predicted aerodynamic cut diameter versus pressure drop and power consumption (adapted from Scrubber Handbook).[8] Lines 1a and 1b are for sieve plates; line 3 is for impingement plate; line 4 is for a packed column; lines 2a and 2b are for venturi scrubbers with f = 0.25, 0.50, respectively. See text.

scrubber itself having a cut diameter around 3 μm. Point C is for the Centrifield. Point D is for the Dynactor. Point P is for the Pentapure. The power is in hydraulic terms for purposes of comparison (same as assuming motor/fan/pump efficiency of 100 percent) where fan or pump power is considered. The Centrifield and Dynactor are comparable in performance to a well-designed venturi with regard to power consumption. The Pentapure and Braxton use more power than other scrubbers for the same efficiency. The Aronetics uses less, if waste heat is "free." If the waste heat energy is included, the Lone Star and Aronetics devices do not differ greatly from the extrapolated cut diameter versus power consumption shown in Figure 45, although such extrapolation is questionable.

SECTION XVI

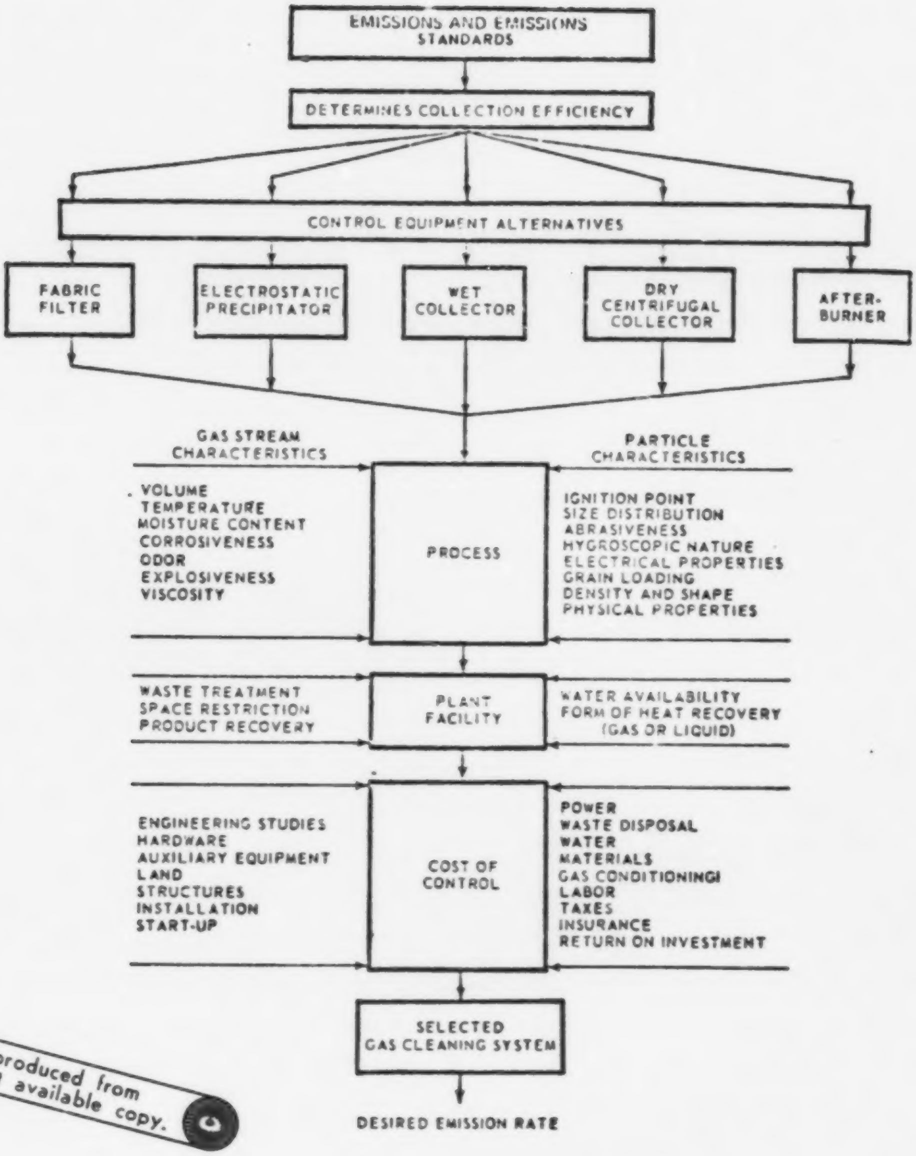
APPLICATIONS

In this section we present some of the considerations that enter into the applicability of a control device. This information is important for potential users of such devices and for those who wish to assess the potential significance of innovations in fine particle control technology.

CONTROL SYSTEMS SELECTION CONSIDERATIONS

Figure 46 is from the HEW document Control Techniques for Particulate Air Pollutants.[37] It summarizes the considerations which apply to the choice of pollution control equipment for particulate emissions reduction. The control goals are usually set by law or by policy of the facility operators.

The controlled emissions will have a mean concentration equal to the mean overall mass efficiency of the control device (See Section XIII) times the mean mass concentration of the uncontrolled emissions. The collection efficiency required and the particle size distribution of the uncontrolled emissions will often limit the control device alternatives. Combustible material may be handled with an afterburner; particulates predominantly larger than 5 or 10 μm can often be controlled to 90 percent or better with a cyclone (dry centrifugal collector); finer particles will generally require either a wet collector (spray, packed bed, etc.) or an electrostatic precipitator or a fabric filter. The alternatives still feasible after evaluation with regard


EMISSIONS AND EMISSIONS STANDARDS
DETERMINES COLLECTION EFFICIENCY
CONTROL EQUIPMENT ALTERNATIVES
FABRIC FILTER
ELECTROSTATIC PRECIPITATOR
WET COLLECTOR
DRY CENTRIFUGAL COLLECTOR
AFTER-BURNER
GAS STREAM CHARACTERISTICS
PARTICLE CHARACTERISTICS
VOLUME
TEMPERATURE
MOISTURE CONTENT
CORROSIVENESS
ODOR
EXPLOSIVENESS
VISCOSITY
PROCESS
IGNITION POINT
SIZE DISTRIBUTION
ABRASIVENESS
HYGROSCOPIC NATURE
ELECTRICAL PROPERTIES
GRAIN LOADING
DENSITY AND SHAPE
PHYSICAL PROPERTIES
WASTE TREATMENT
SPACE RESTRICTION
PRODUCT RECOVERY
PLANT FACILITY
WATER AVAILABILITY
FORM OF HEAT RECOVERY (GAS OR LIQUID)
ENGINEERING STUDIES
HARDWARE
AUXILIARY EQUIPMENT
LAND
STRUCTURES
INSTALLATION
START-UP
COST OF CONTROL
POWER
WASTE DISPOSAL
WATER
MATERIALS
GAS CONDITIONINGI
LABOR
TAXES
INSURANCE
RETURN ON INVESTMENT
SELECTED GAS CLEANING SYSTEM
DESIRED EMISSION RATE

Reproduced from best available copy.

Figure 46. Criteria for selection of gas cleaning equipment[37]

to collection efficiency will then have to be compared with respect to process parameters, available facilities, control costs. Once the evaluation has been made, a cleaning system type may emerge as best. The same kind of evaluation would then be repeated for various candidates of this type, probably employing methods for cost, power, and efficiency analysis similar to those in Sections XIII, XIV and XV.

COMPARISONS

From the same HEW reference[37] is Table 14 which gives brief comparisons of the advantages and disadvantages of settling chambers (gravitational collectors), cyclones, wet collectors, electrostatic precipitators, and fabric filters. Table 15 comes from Strauss;[16] it makes a somewhat more general comparison between those devices which collect particles dry (most filters, cyclones, most electrostatic precipitators) and those which collect them wet (scrubbers, some electrostatic precipitators, water-washed filters). If one type of control device were clearly superior for all applications, manufacturers of the other types would not not stay in business for long; the continued use of all these control types is evidence that for specific applications each has advantages that make it preferable to the other alternatives. The potential user should investigate the various alternatives rather fully.

Most of the novel control devices are variations on the theme of wet scrubbing. As Calvert et al.[9] note in the Scrubber Handbook, scrubbers as a group have the following advantages and disadvantages, generally: capital cost is relatively low; explosions are unlikely; they are small and simple; the particulate material is removed continuously. On the other hand, operating costs are relatively high; often the efficiencies are substantially less than 90 percent on particles between 0.1 and 1 μm; water treatment is required; clogging, corrosion, and erosion can be problems; cooling the gas and increasing its volume (water vapor) may be

Table 14. ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES[37]

Collector	Advantages	Disadvantages
Gravitational	Low pressure loss, simplicity of design and maintainance.	Much space required. Low collection efficiency.
Cyclone	Simplicity of design and maintainance Little floor space required Dry continuous disposal of collected dusts	Much head room required. Low collection efficiency of small particles. Sensitive to variable dust loadings and flow rates.
	Low to moderate pressure loss. Handles large particles. Handles high dust loadings. Temperature independent.	
Wet collectors	Simultaneous gas absorption and particle removal.	Corrosion, erosion problems. Added cost of wastewater treatment and reclamation.
	Ability to cool and clean high-temperature, moisture-laden gases. Corrosive gases and mists can be recovered and neutralized. Reduced dust explosion risk Efficiency can be varied	Contamination of effluent stream by liquid entrainment. Freezing problems in cold weather Reduction in buoyancy and plume rise. Water vapor contributes to visible plume under some atmospheric conditions.
Electrostatic precipitator	99 + percent efficiency obtainable	Relatively high initial cost.
	Very small particles can be collected	Precipitators are sensitive to variable dust loadings or flow rates.
	Particles may be collected wet or dry	Resistivity causes some material to be economically uncollectable.
	Pressure drops and power requirements are small compared to other high-efficiency collectors.	Precautions are required to safeguard personnel from high voltage.
	Maintenance is nominal unless corrosive or adhesive materials are handled. Few moving parts Can be operated at high temperatures (550° to 850°F.).	Collection efficiencies can deteriorate gradually and imperceptibly.
Fabric filtration	Dry collection possible Decrease of performance is noticeable	Sensitivity to filtering velocity. High-temperature gases must be cooled to 200° to 550°F.
	Collection of small particles possible High efficiencies possible	Affected by relative humidity (condensation). Susceptibility of fabric to chemical attack.

Table 15. ADVANTAGES AND DISADVANTAGES OF WET AND DRY COLLECTORS[16]

Wet collectors	Dry collectors
Advantages:	Advantages:
1. Can collect gases and particles at the same time.	1. Recovery of dry material may give final product without further treatment.
2. Recovers soluble material, and the material can be pumped to another plant for further treatment.	2. Freedom from corrosion in most cases.
3. High temperature gases cooled and washed.	3. Less storage capacity required for product.
4. Corrosive gases and mists can be recovered and neutralized.	4. Combustible filters may be used for radioactive wastes.
5. No fire or explosion hazard if suitable scrubbing liquor used (usually water).	5. Particles greater than 0.05 microns may be collected with long equipment life and high collection efficiency.
6. Plant generally small in size compared to dry collectors such as baghouses or electrostatic precipitators.	
Disadvantages:	Disadvantages:
1. Soluble materials must be recrystallized.	1. Hygroscopic materials may form solid cake and be difficult to shake off.
2. Insoluble materials require settling in filtration plant.	2. Maintenance of plant and disposal of dry dust may be dangerous to operatives.
3. Waste liquids require disposal which may be difficult.	3. High temperatures may limit means of collection.
4. Mists and vapours may be entrained in effluent gas streams.	4. Limitation of use for corrosive mists for some plants (e.g., baghouses).
5. Washed air will be saturated with liquid vapour, have high humidity and low dew point.	5. Creation of secondary dust problem during disposal of dust.
6. Very small particles (sub-micron sizes) are difficult to wet, and so will pass through plant.	
7. Corrosion problems.	
8. Liquid may freeze in cold weather.	

undesirable. The emphasis of most innovations in scrubber technology presented here as novel control devices has been to increase collection efficiency or decrease operating cost (power) or both.

EXTANT APPLICATIONS

Assuming that current users of control devices have generally made rational choices in the systems employed, one could gauge the applicability of a control method on the uses to which it is now being put. Table 16 displays a list of ten major industries with the control devices used predominantly.[37] Clearly, the inventors of novel control devices would hope that their innovations would extend the applicability of their device to new industries or make it the method of choice from among similar methods in an industry already employing particulate pollution control. The prospective user will have to evaluate control devices for his particular application.

SUMMARY

The principal considerations which apply to the selection of a control system have been listed and discussed briefly. The major features of the different types of control devices have been compared to help narrow the field of candidate devices for a given application. Some examples of current use are presented, with the caution that the prospective user will want to assess the wisdom of the choice made by others, as well as the degree to which his requirements resemble theirs, and the extent to which the prospective control device resembles those already in use. No choice should be made without a thorough engineering analysis.

Table 16. INDUSTRIAL PROCESS AND CONTROL SUMMARY[37]

Industry or process	Source of emissions	Particulate matter	Method of control
Iron and steel mills	Blast furnaces, steel making furnaces, sintering machines.	Iron oxide, dust, smoke	Cyclones, baghouses, electrostatic precipitators, wet collectors.
Gray iron foundries	Cupolas, shake out systems, core making.	Iron oxide, dust, smoke, oil, grease, metal fumes.	Scrubbers, dry centrifugal collectors.
Metallurgical (non-ferrous)	Smelters and furnaces	Smoke, metal fumes, oil, grease.	Electrostatic precipitators, fabric filters.
Petroleum refineries	Catalyst regenerators, sludge incinerators.	Catalyst dust, ash from sludge.	High-efficiency cyclones, electrostatic precipitators, scrubbing towers, baghouses.
Portland cement	Kilns, dryers, material handling systems.	Alkali and process dusts	Fabric filters, electrostatic precipitators, mechanical collectors.
Kraft paper mills	Chemical recovery furnaces,	Chemical dusts	Electrostatic precipitators, venturi scrubbers.
Acid manufacture-phosphoric, sulfuric.	Thermal processes, phosphate rock acidulating, grinding and handling systems.	Acid mist, dust	Electrostatic precipitators, mesh mist eliminators.
Coke manufacturing	Charging and discharging oven cells, quenching, materials handling.	Coal and coke dusts, coal tars.	Meticulous design, operation, and maintenance.
Glass and glass fiber	Raw materials handling, glass furnaces, fiberglas forming and curing.	Sulfuric acid mist, raw materials dusts, alkaline oxides, resin aerosols.	Glass fabric filters, afterburners.
Coffee processing	Roasters, spray dryers, waste heat boilers, coolers, conveying equipment.	Chaff, oil aerosols, ash from chaff burning, dehydrated coffee dusts.	Cyclones, afterburners, fabric filters.

Reproduced from best available copy.

SECTION XVII

COLLECTION EFFICIENCY THEORY

Each of the novel devices tested in the IERL program is of the group of particle collection devices which work by using the collection of particles on obstacles placed in the flow: e.g., spray scrubbers, high porosity beds, high porosity filters. Another group is more suitably viewed as doing their collection in channels: electrostatic precipitators, cyclones, sedimentation chambers, and low porosity filters and beds. The analysis which follows is for the first group, and to simplify description we have called the device a "scrubber" and labelled the collection obstacles as "droplets," but the generality of the approach should not be ignored.

This analysis, influenced by those of Knettig and Beeckmans[38] and Calvert et al.,[9] starts with the volume of particle-laden gas per unit time, dQ_s, which sweeps past droplets having a number concentration n_d and individual cross-sectional areas A_d contained in the small volume A dx, where dx is a distance measured parallel to the flow (see Figure 47). This volume rate of "sweeping" or scrubbing is:

$$dQ_s = (u_g - u_d)\, n_d\, A_d\, A\, dx \qquad (1)$$

where u_g = gas velocity, cm/s

u_d = droplet velocity, cm/s.

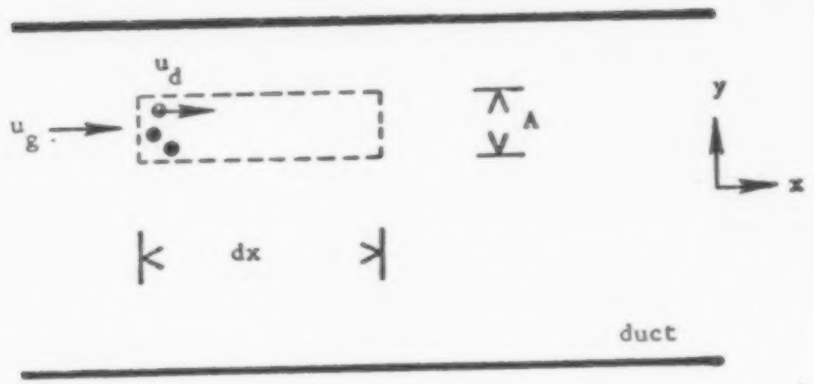

u_d
u_g
A
y
x
dx
duct

Figure 47. Geometry for collector analysis

The rate of particle removal due to this "sweeping" is:

$$A\ u_g\ dc = -\ \eta\ c\ dQ_s$$

$$= -\ \eta\ c\ (u_g - u_d)\ n_d\ A_d\ A\ dx$$

where η = single droplet collection efficiency

c = particle concentration, cm^{-3}

or (Knettig and Beeckmans):[38]

$$\frac{dc}{c} = -\ \eta \left[\frac{(u_g - u_d)}{u_g}\right] n_d\ A_d\ dx \qquad (2)$$

From this point, the derivation can be done with various degrees of sophistication:

1. The calculation of the single droplet efficiency η can include some or all of the following mechanisms:

   impaction
   interception
   diffusion
   electrostatic interactions
   diffusiophoresis
   thermophoresis

2. The velocities u_g and u_d can be calculated in detail including their dependence on position, measured parallel to and perpendicular to the mean gas flow.

3. The spatial variation of n_d can be taken into account.

4. Various averages of droplet areas, A_d, can be used, or a functional form for their distribution employed.

If the various quantities in the right-hand-side of equation (2) are independent of position, then:

$$\frac{c}{c_o} = \exp\left(- \eta \left[\frac{u_g - u_d}{u_g}\right] n_d A_d L \right) \tag{3}$$

where c_o = concentration at $x = 0$

c = concentration at $x = L$

Droplet Concentration

One model for the concentration of the droplets, n_d, is just the volume of droplets supplied per unit time, Q_d, divided by the average volume per droplet V_d, divided also by the volume rate of gas flow Q_g:

$$n_d = Q_d/V_d \; Q_g \tag{4}$$

(For packed beds, Q_d/Q_g is replaced by the solids fraction). For spherical droplets of a single diameter (D_d), $n_d A_d$ becomes:

$$n_d A_d = \frac{Q_d}{\frac{\pi}{6} D_d^3 Q_g} \left(\frac{\pi}{4} D_d^2\right) = \frac{3}{2} \left(\frac{Q_d}{Q_g}\right) \frac{1}{D_d} \tag{5a}$$

If this is combined with an empirically obtained factor, f, for $(u_g - u_d) / u_g$, one has:

$$\frac{c}{c_o} = \exp\left[- \frac{3}{2} \eta f \frac{Q_d}{Q_g} \frac{L}{D_d}\right] \tag{5b}$$

It can be shown that in calculating penetration when one uses an average value for the argument of the exponent in equation (3), the ratio c/c_o thus calculated is less than when c/c_o values are calculated from each value of the argument and then averaged (which is much closer to the actual physical situation). The greater the dispersion of the values appropriate for the argument of equation (3), the greater the difference between the value calculated by using an average and the value appropriate to the situation. For a scrubber, this means that for droplet distributions having an optimal average cross-sectional area, the distribution having the smallest standard deviation of size would be most efficient. The same could be said about the advantage of flow and droplet concentration uniformity.

The concentration of collectors in a bed or a filter is fairly uniform, but this is often not true in a spray scrubber. Although the droplet concentration is usually calculated by using equation (4), which involves the ratio of the spray volume flow to the gas volume flow, this is not strictly correct. In steady state, the volume flow of droplets through the complete cross-sectional area of the duct, A*, is equal to the injected spray volume flow, Q_d:

$$Q_d = A^* \, \overline{u_d} \, \overline{n_d} \, V_d, \tag{6}$$

the product of the area, the average droplet velocity, the average number concentration, and average single droplet volume. This means that the average concentration at A* is:

$$\overline{n_d} = Q_d / A^* \, \overline{u_d} \, V_d \tag{7a}$$

$$= Q_d \, \overline{u}_g / Q_g \, u_d \, V_d \tag{7b}$$

not

$$Q_d / A^* u_g V_d = Q_d / Q_g V_d \tag{7c}$$

which is from equation (4).

Thus, where the droplets are moving faster than the gas, their concentration will be less than equation (4) predicts, and where they are moving more slowly than the gas, their concentration will be greater. In general, this indicates that, other things being equal, scrubbing becomes more intense when the gas is accelerating and less intense where the gas is decelerating (because the droplet motion lags behind the gas motion).

The incorporation of equation (7a) into equation (3) yields:

$$c/c_o = \exp \left[- \eta \frac{u_g - u_d}{u_d} \left(Q_d / Q_g \right) \frac{A_d L}{V_d} \right] \tag{8}$$

Relative Velocities

In some circumstances we may be able to calculate $\left[(u_g - u_d)/u_d \right]$, but often it is just estimated.

Droplet (Obstacle) Areas

If all droplets have the same cross-sectional area, A_d, then this is simple. If not, one may want to use a distribution of droplet cross-sections $f(A_d)$

where $\int_0^\infty f(A_d) A_d \, dA_d = \bar{A}_d$ (9)

the average cross-sectional area.

Single Droplet Efficiency

As noted the single droplet efficiency η involves a number of physical mechanisms. It is defined as:

$$\eta = \frac{\text{flow area cleaned per collector}}{\text{collector cross-sectional area}} \tag{10a}$$

$$\eta = A_c/A_d \tag{10b}$$

This is shown in Figure 48. The dotted lines are representations of the trajectories of particles just barely captured, the limiting trajectories.

The calculation of the single particle efficiency, η, depends in part upon the flow past the collector (droplet, fiber, etc.). There are two flow models commonly in use: viscous flow and potential flow. Viscous flow is an appropriate model when the obstacle Reynolds number is small; that is, when:

$$Re_d = \rho\ (u_g - u_d)\ D_d\ /\mu \ll 1 \tag{11}$$

where ρ = gas density = 1.2×10^{-3} g/cm^3 for air at room temperature and pressure

μ = gas viscosity = 1.8×10^{-4} poise for air at room temperature and pressure.

Although the motion of the dust particles in the gas stream often meets this Reynolds number criterion, collectors usually do not. A flow of 10 cm/s (20 fpm) past a fiber or droplet 100 μm in diameter gives $Re_d \sim 1$. The model of potential flow is derived for $Re_d \gg 1$, but even in this regime it is appropriate only up to near the point on the collector surface where the flow separates and forms a wake, which trails behind the obstacle. Although we will work with the potential flow approximation, its limitation should be appreciated. For those

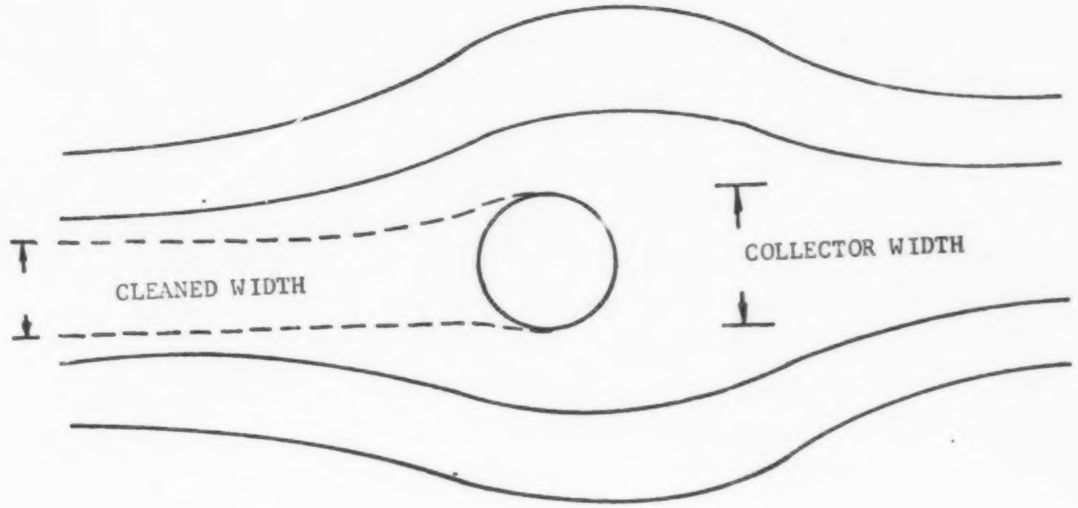

CLEANED WIDTH
COLLECTOR WIDTH

Figure 48. Flow streamlines and the limiting trajectories

phenomena in which the collection occurs on the upstream half of the obstacle, it should work well; for those with a contribution from the downstream side, such as the case for electrical attraction, the model is not strictly appropriate, though in use.[39]

The single particle efficiency can be calculated for various collection mechanisms separately and then combined as though the mechanisms acted independently (Knettig and Beeckmans)[38], but this is not generally correct. The better, though more difficult, manner for handling the contributions of several collection mechanisms is to solve the particle trajectory equations in the appropriate flow field including the collection forces and mechanisms, as done by Sparks[40] and George and Poehlein,[39] among others. The disadvantage of the correct approach is that it would require a great many such calculations, one each for every specific situation of interest. This disadvantage is partially circumvented by doing such calculations for a number of combinations of parameters of interest and then interpolating from the results. Where such calculations are available, one can use them; otherwise one must employ other methods for combining the effects of different mechanisms, simplifying the procedure whenever possible by neglecting mechanisms which are much smaller than the primary collection mechanisms for the particular situation. A justification for using equation (3) even though its assumptions are not met in practice is that the accuracy to which the other components in its argument are known is not great, so that using them in a more accurate expression than equation (3) would be gilding the lily, and more difficult than the situation warrants.

Impaction - When a dust particle strikes the collection surface because of its inertia and its inability to follow the gas streamlines, the collection is said to be due to impaction. Particles in a moving stream will impact upon a deflecting surface provided that the inertia of the particles is sufficient to overcome the drag exerted by the air stream deflected by the impaction surface. The impaction process can be characterized by the impaction parameter ψ which is defined by the following expression:

$$\psi = \frac{C \rho_p v d_p^2}{18 \mu D_d} \tag{12}$$

where ρ_p = particle density

v = gas velocity

d_p = particle diameter

μ = gas coefficient of viscosity

D_d = droplet diameter

C = Cunningham correction factor defined empirically as:

$$C = 1 + 2.492 \lambda/d_p + 0.84 (\lambda/d_p) \exp(-0.435\, d/\lambda)$$

where λ is the molecular mean free path.

The following expression has been found, empirically, to approximate the single droplet efficiency for impaction:[8]

$$\eta_I = \psi^2 / (\Psi + 0.35)^2 \tag{14}$$

In Table 17 are listed several values of η_I along with the calculated values from equation (14) and the results reported by May and Clifford.[41] The agreement seems sufficient for most purposes.

Table 17. CALCULATED η_I COMPARED WITH DATA

ψ	η_I	Experimental data[41]
0.01	0.0008	-
0.03	0.0062	-
0.1	0.049	0.03
0.3	0.213	0.3
1.0	0.549	0.6
3.0	0.802	0.75
10.0	0.934	0.94
30.0	0.977	-

Interception - Particles whose centers move along flow streamlines may still strike the obstacle (droplet, fiber) because of their width perpendicular to their motion, in which case collection is said to be via interception. The parameter which indicates the magnitude of this effect is N_R, the ratio of particle radius to collector radius (spherical or cylindrical collectors). The incremental efficiency due to this effect lies between $2N_R$ and $3N_R$ for potential flow around a sphere and between N_R and $2N_R$ for potential flow around a cylinder (Fuchs)[42] for inertialless and highly massive particles, respectively.

Diffusion - The Brownian motion of particles causes there to be a net diffusive flux of particles from regions of higher concentration to regions of lower concentrations and from a gas stream to adjacent surfaces, if some or all of the particles adhere to the surfaces. The Peclet number, Pe, measures the relative amount of convective transport to diffusive transport for a moving gas stream:

$$Pe = u_g\ D_d / D = Re_d\ Sc \qquad (15)$$

where D = diffusivity, cm^2/s

= $kTC/3\pi\mu d_p$ for $d_p \gtrsim 0.01$ μm

k = Boltzmann constant

T = absolute temperature

Sc = Schmidt number = $\mu/D\rho$

Diffusion is substantial when $Pe \ll 1$.

As discussed more fully by Strauss,[16] combining these mechanisms and forming an appropriate single particle efficiency η_{ICD} for their combination is difficult, but experimental evidence supports well the use of the following equation:

$$\eta_{ICD} = 6\ Sc^{-2/3}\ Re^{-1/2} + 3N_R^{\ 2}\ Re^{1/2} \tag{16}$$

Figure 48a is taken from the book by Strauss[16] to show the agreement between experimental η_{ICD}'s and this expression. The second term on the right-hand-side is equivalent to $(54\ N_R^{\ 2}\ \psi)^{1/2}$, and dominates where impaction is important. Diffusion is rarely important for particles of diameter > 0.5 μm, so this equation is worth using only for particles smaller than 0.5 μm. For larger particles equation (14) should suffice.

Electrostatic Attraction - The two major types of electrostatic force significant in particle collection are the Coulomb force a charged particle is subjected to in an electric field and the induced charge (dipole)

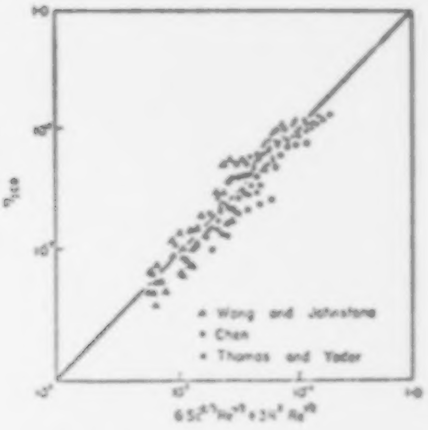


Figure 48a. Combined collection efficiency based on experimental results η_{ICD} versus $(6Sc^{-2/3}\ Re^{-1/2} + 3Re^{1/2}\ R^2)$.[16] $(R = N_R.)$

force created by an inhomogeneous electric field. The Coulomb force is given by the equation

$$F_c = q_p\ E \tag{16}$$

where q_p = particle charge, coul or stat-coul

E = electric field, v/m or stat-v/cm

The force due to induced polarization in an inhomogeneous electric field is

$$F = x_E\ V_p \text{ grad } (E^2) \tag{17}$$

where $x_E = (3\pi/8)\ (\epsilon_p - 1)/(\epsilon_p + 2)$ for a sphere

ϵ_p = dielectric constant of particle

V_p = particle volume.

Because the gradient of a homogeneous field is zero, this second force is only operative in inhomogeneous fields, such as those close to a charged nonplanar collector.

Generally, particles are charged for electrostatic precipitation by having them pass through a region of high ion concentration (N, ions/cm^3) during which time, t, they approach an equilibrium charge, q_p (stat-coul). The approach to equilibrium has the time dependence $(1 + t_e/t)^{-1}$ where the equilibrium time at 20°C and 1 atm is

$$t_e = 1.0 \times 10^6 \; N^{-1} \text{ seconds.} \qquad (18)$$

Many particles behave as though they were conductors during the time scales of interest. Furthermore, control device designs usually assure sufficiently long residence times, $t \gg t_e$. Under such conditions Cochet's equation for charge is:[21]

$$q_p \doteq \left[(1 + 2\lambda'/d_p)^2 + 2(1 + 2\lambda'/d_p)^{-1}\right]\left[E d_p^{\,2}/4\right] \qquad (19)$$

where $\lambda' = 0.1 \times 10^{-4}$cm.

For $d_p \gtrsim 1$ μm,

$$q_p = 3 \, E \, d_p^{\,2}/4. \qquad (20)$$

The above equations enable determination of the particle charge with several different degrees of sophistication. Table 18 has been calculated using the next-to-last equation above, and is taken from work by Cooper.[24]

Table 18. APPROXIMATE PARTICLE CHARGE (COCHET EQUATION)
(CONDUCTING PARTICLES; E = 10 kV/cm = 33.3 esu)

Particle diameter, d_p, (μm)	Particle charge, q_p, (esu)	Number of electrons
0.1	8.05×10^{-9}	16.8
0.3	2.80×10^{-8}	58.3
1.0	2.59×10^{-7}	539.6
3.0	2.26×10^{-6}	4.7×10^{3}
10.0	2.50×10^{-5}	5.2×10^{4}

The Coulomb force is proportional to the electric field. In practice, it is difficult to get fields that are very much stronger than 33 statvolt/cm (10 kV/cm) because of electrical breakdown of air at such high fields. This value has been used to calculate reasonable upper limits on particle migration velocities.

The induced polarization force is proportional to the gradient of the field, which can be estimated for spheres or cylinders by the field at the surface divided by the radius, as we have done.

Figure 49 (from Cooper[23]) shows the results of calculations of migration velocities assuming maximum particle charges, fields, and field gradients, as indicated above, for particles of the size indicated being collected by a 100 μm spherical collector. The case of charged particle and charged collector produced the largest migration velocities, followed by charged collector with uncharged particles; charged particles with uncharged collector; and mutual repulsion of charged particles in the vicinity of an uncharged collector, assuming maximum charge, mass median diameter indicated, mass concentration of $1 g/m^3$, and particles of unit density.

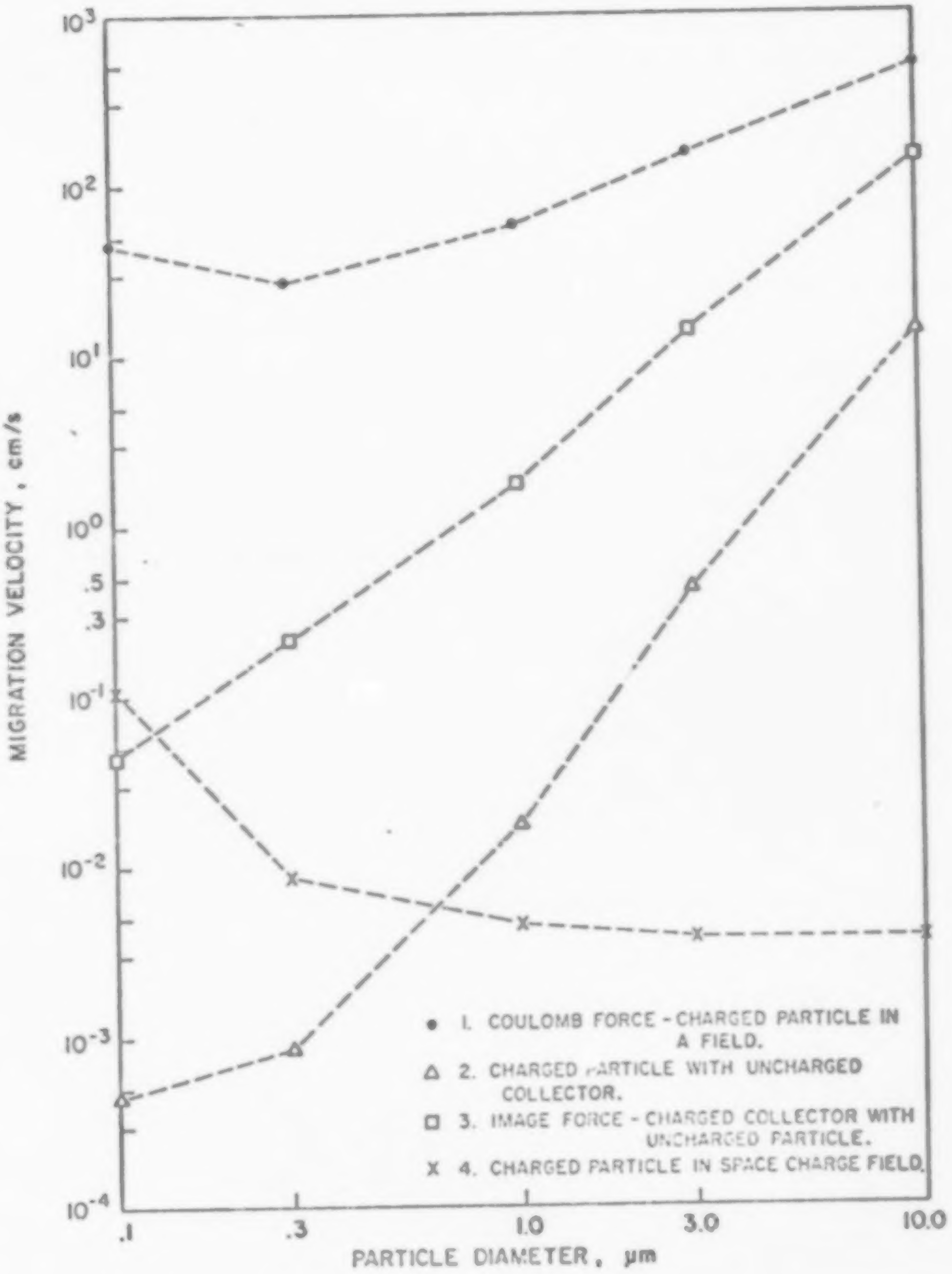


Figure 49. Theoretically calculated migration velocities for four electrostatic mechanisms versus particle diameter

The migration velocity, w, is defined so that the product of migration velocity and collector surface area, A_s, is the same as the product of the target efficiency and relative velocity and collector cross-sectional area,

$$w\, A_s = \eta\, (u_g - u_d)\, A_d, \tag{21}$$

a definition which breaks down for $u_g = u_d$.

For electrostatic collection, the migration velocity is independent of u_g and u_d; it is the terminal velocity at which the fluid drag force on the particle equals the electrostatic force. Because A_s and A_d are the same order of magnitude, electrostatic migration will be at least as important as the aforementioned mechanisms where

$$w/\eta_{ICD}\, (u_g - u_d) \gtrsim 1. \tag{22}$$

For collection to be appreciable, one also needs

$$w\, (\Sigma A_s)\, /\, Q_g \gtrsim 1. \tag{23}$$

Here ΣA_s is the total collection surface area.

Figure 49 allows an estimation of w.

Path Length, L

If the collectors are a fixed bed, then its length parallel to flow is used as L in equation (8). If a spray or other moving spherical collectors are used, then L is the net travel distance with respect to the gas undergone by the collectors. The net distance is determined by the drag coefficient, C_D, where

$$C_D = 2\ F_D/\rho(u_d - u_g)^2\ A_d \tag{24}$$

in which

$$F_D = \text{arag force.} \tag{25}$$

For $Re_d < 1$,

$$C_D = 24/Re_d, \tag{26}$$

and for accelerating spheres with Re_d between 6 and 400, Ingebo[43] found the drag coefficient to be

$$C_D^* \doteq 55/Re_d. \tag{27}$$

For particles obeying $C_D = 24/Re_d$ (Stokes law), it has been shown by Fuchs[43]

$$L = |u_p - u_g|_o t \tag{28}$$

$$t = C\rho\ d_p^{\ 2}/18\ \mu$$

and $|u_p - u_g|_o$ is the initial velocity difference. If C_D^* were valid throughout the particle motion, then it would be true that

$$t^* = (24/55)\ t = 0.44t, \tag{29}$$

$$L = |u_p - u_g|_o\ t^*. \tag{30}$$

An approximation scheme should suffice, using the following formulas, depending upon initial Re_d:

$$Re_d \leqslant 1 \qquad t = C\rho \, d_p^2/18\,\mu \tag{31}$$

$$1 < Re_d \leqslant 10 \qquad t^* = 0.72\ t \tag{32}$$

$$10 < Re_d \leqslant 400 \qquad t^* = 0.44\ t \tag{33}$$

For scrubbers, L increases with droplet size and with initial velocity differences.

SUMMARY

The calculation of collection efficiency for a given system can be quite difficult, despite the availability of the theoretical expressions. Theory is valuable, however, in showing what factors enhance or interfere with collection efficiency and indicating how strongly efficiency is dependent upon the factors.

Those who wish more information on the following topics should consult the indicated references:

Aerosol Behavior - Fuchs, *Mechanics of Aerosols*;[42] Green and Lane, *Particulate Clouds*;[44] Davies, *Aerosol Science*[45]

Filtration - Davies, *Air Filtration*;[46] Billings and Wilder, *Handbook of Fabric Filtration Technology*;[47] *Journal of Air Pollution Control Association, 24* (12), December 1974

Scrubbing - Calvert et al., *Scrubber Handbook*;[8] Strauss *Industrial Air Pollution Control*;[16] *Journal of the Air Pollution Control Association, 24* (10), October 1974

Electrostatic Precipitation - White, *Industrial Electrostatic Precipitation*;[21] Oglesby and Nichols, *A Manual of Electrostatic Precipitator Technology*;[48] *Journal of the Air Pollution Control Association, 25* (2), February 1975

SECTION XVIII

APPENDIX: AERODYNAMIC DIAMETER DEFINITION

In expressing particle size, we have often used "aerodynamic diameter" rather than geometrical diameter, especially in discussing collection efficiency as a function of particle size. For situations such as gravitational settling and inertial impaction where the force on the particle is proportional to its mass, aerodynamic diameter is the particle "size" which governs its motion.

Stober[50] discussed the origin of the term. He also gave a clear definition: "the diameter of a sphere of unit density ($\rho_o = 1.0\ g/cm^3$) attaining at low Reynolds numbers in still air the same final settling velocity as the actual particle under consideration." As he noted, this parameter is of physical interest and can be obtained by measurements in some cases where other measures of particle size and density are not obtainable. This definition means that the particle terminal settling velocity, v_s, can be used to obtain the aerodynamic diameter, d_{ae}:

$$v_s = g\ C(d_{ae})\ \rho_o\ d_{ae}^{\ 2}/18\ \mu \quad . \qquad (34)$$

for Stokes law settling (particle Reynolds number < 1).

Similarly, the aerodynamic diameter can be measured by impaction efficiency under known conditions. If the particle is a sphere with diameter d_p, then the following relationship holds:

$$C(d_{ae})\ \rho_o\ d_{ae}^{\ 2} = C(d_p)\ \rho_p\ d_p^{\ 2}, \qquad (35)$$

where $C(d)$ = Cunningham slip correction factor;
$\doteq 1 + (0.16\ \mu m)/d$, at normal temperature and pressure (25°C, 1 atm),

and the appropriate diameter, d, must be used in each calculation of C.

Given the aerodynamic diameter or the particle diameter and density, collection by gravitational settling, centrifugal sedimentation, or inertial impaction can be readily calculated from available formulas.

It is not generally recognized, however, that going from particle diameter and density to particle aerodynamic diameter or vice-versa is not routine; for example, where the Cunningham correction is appreciable,

$$d_{ae} \neq \sqrt{C(d_p)\ \rho_p}\ \ d_p. \qquad (36)$$

The Scrubber Handbook,[8] it should be noted, defines an "aerodynamic diameter" as:

$$d_{pa} = \sqrt{C(d_p)\ \rho_p}\ \ d_p \qquad (37)$$

and seems to use this definition consistently, even though recognizing the unusual units it implies, $cm(g/cm^3)^{1/2}$.

To go from particle diameter and density to aerodynamic diameter or vice-versa must be done by solving the equation

$$C(d_{ae})\ \rho_o\ d_{ae}^{\ 2} = C(d_p)\ \rho_p\ d_p^{\ 2}. \qquad (38)$$

This can be done in two fairly easy ways:

a) Using the formula for the Cunningham correction given here, one obtains a quadratic equation in powers of the diameter sought, d:

$$ad^2 + bd = -c \tag{39}$$

the solution to which is the well-known formula

$$d = (-b \pm (b^2 - 4ac)^{1/2})/2a. \tag{40}$$

b) Setting the unknown value of the Cunningham correction equal to one, $C \doteq 1$, the first approximation to the unknown diameter, d_1, is obtained from Equation (38); then this first approximation is used to evaluate the unknown Cunningham correction factor $C(d_1)$ and a second approximate solution, d_2, is obtained, also from equation (38). A third approximation, d_3, using the d_2 value for the unknown diameter, is rarely needed.

SECTION XIX

REFERENCES

1. McCain, J. D. Evaluation of Aronetics Two-Phase Jet Scrubber. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-74-129. December 1974.

2. Dennis, R., R. Bradway, and R. Cass. Braxton Sonic Agglomerator Evaluation. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-74-036. May 1974.

3. Leith, D. and D. Mehta. Cyclone Performance and Design. Atmospheric Environment, Pergamon Press. 7:527-549. 1973.

4. Calvert, S. Engineering Design of Wet Scrubbers. J APCA. 24:929-934. 1974.

5. McCain, J. D. Evaluation of Centrifield Scrubber. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-74-129-a. June 1975.

6. Calvert, S., J. Rowan, and C. Lake. Experimental Tests of Novel Fine Particulate Collection Devices. Preliminary Report. Contract No. 68-02-1496. Task Order No. 1. January 13, 1975.

7. Cooper, D. W. and D. P. Anderson. Dynactor Scrubber Evaluation. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-74-083-a. June 1975.

8. Calvert, S., J. Goldschmid, D. Leith, and D. Mehta. Scrubber Handbook. Control Systems Division, Office of Air Programs. U.S. Environmental Protection Agency, Research Triangle Park, N. C. 1972.

9. Lancaster, B. W. and W. Strauss. A Study of Steam Injection Into Wet Scrubbers. Ind Eng Chem Fundamentals. 10(3):362-369. March 1971.

10. Lohs, W. Manufacture of Aerosols and Separation of Ultrafine Dusts in Spray Washers. Staub, 29(2):43. 1969.

11. Calvert, S., D. Lundgren, and D. S. Mehta. Venturi Scrubber Performance. J Air Pollut Contr Assoc. 22:529-532. 1972.

12. Bird, R. B., W. E. Stewart, and E. N. Lightfoot. Transport Phenomena. Wiley, New York. 1960.

13. McCain, J.D., and W.B. Smith. Lone Star Steel Steam-Hydro Air Cleaning System Evaluation. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-74-028. April 1974.

14. Ananth, K.P. Evaluation of the Mystaire Scrubber. Draft of Final Report. EPA Contract No. 68-02-1324, Task Order No. 7., for Control Systems Laboratory. Office of Research and Development. U.S. Environmental Protection Agency.

15. Carpenter, C. L. and D. F. Othmer. Entrainment Removal by a Wire-Mesh Separator. A.I.Ch.E.J. 1:549-557. 1955.

16. Strauss, W. Industrial Gas Cleaning. Pergamon, New York. 1966.

17. Cooper, D.W. Pentapure Impinger Evaluation. Office of Research and Development. U.S. Environmental Protection Agency. EPA-650/2-75-024a. March 1975.

18. Ananth, K.P., Evaluation of the Pentapure Impinger. Final Report. EPA Contract No. 68-02-1324, Task Order No. 6., for Control Systems Laboratory. Office of Research and Development. EPA.

19. Greene, F.T., L.J. Shannon. Evaluation of Electrostatic Droplet Scrubber. Contract No. 68-02-1324, Task Order No. 16., for Control Systems Laboratory. Office of Research and Development. EPA.

20. Pilat, M. J. Collection of Aerosol Particles by Electrostatic Droplet Scrubbers. J Air Pollut Contr Assoc. 25:176-179. 1975.

21. White, H. J. Industrial Electrostatic Precipitation. Pergamon, New York, 1963.

22. Pilat, M. J., S. A. Jaasund, and L. E. Sparks. Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers. Environ Sci & Technol. 4:360. 1974.

23. Cooper, D. W., Fine Particle Control by Electrostatic Augmentation of Existing Methods. Paper No. 75-02.1 presented at the 68th Annual Meeting of the Air Pollution Control Association. Boston, Mass. June 1975.

24. Sparks, L. E., and M. J. Pilat. Effect of Diffusiophoresis on Particle Collection by Wet Scrubbers. Atmos Environ. 4:651-660. 1970.

25. Lippman, M. Respirable Dust Sampling. Am Indus Hyg Assoc J. 31:138. 1970.

26. Friedlander, S. K. Small Particles in Air Pose a Big Control Problem. Environ Sci & Technol. 7:1115-1118. 1973.

27. Edmisten, N. G., and F. L. Bunyard. A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources. J Air Pollut Contr Assoc. 20:446-452. 1970.

28. Hanf, E. M., and J. W. MacDonald. Economic Evaluation of Wet Scrubbers. Chem Eng Prog. 7(3):48-52. 1975.

29. Fraser, M. D., and D. R. Eaton. Cost Models for Venturi Scrubber System. Presented at 68th Annual Meeting of APCA, Boston, Mass. 1975.

30. Fraser, M. D., and G. J. Foley. Cost Model for Fabric Filter Systems. Presented at 67th Annual Meeting of the APCA. Denver, Colorado. 1974.

31. McKenna, J. D. Applying Fabric Filtration to Coal-Fired Boilers. Environmental Protection Agency Report EPA-650/2-74-058. July 1974.

32. Schneider, G. G., et al. Selecting and Specifying Electrostatic Precipitators. Chem Eng. 94-108. May 26, 1975.

33. Benson, J. R., and M. Corn. Costs of Air Cleaning With Electrostatic Precipitators at TVA Steam Power Plants. J Air Pollut Contr Assoc. 24(4):340-348. 1974.

34. Eckenfelder, W. W., Jr. Industrial Water Pollution Control. McGraw-Hill. 1966.

35. Eckenfelder, W. W., Jr. Water Quality Engineering for Practicing Engineers. Barnes and Noble. 1970.

36. Greco, J. R. Transfer Station Feasibility is Measured Against Direct Haul. Solid Wastes Management. 17. April 1974.

37. Control Technology for Particulate Air Pollution. U.S. Department of Health, Education and Welfare. Washington, D.C. January 1969.

38. Knettig, P. and J.M. Beechmans. Inertial Capture of Aerosol Particles by Swarms of Accelerating Spheres. J Aerosol Sci. 5:225. 1974.

39. George, H. F., and G. W. Poehlein. Capture of Aerosol Particles by Spherical Collectors: Electrostatic, Inertial, Interception, and Viscous Effects. Environ Sci & Technol. 8:46. 1974.

40. Sparks, L. E. The Effect of Scrubber Operating and Design Parameters on the Collection of Particulate Air Pollutants. Ph.D. Dissertation (Civil Engineering) University of Washington, 1971.

41. May, K. R. and R. Clifford. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons, and Discs. Ann Occup Hyg. 10:83-95. 1967.

42. Fuchs, N. A. The Mechanics of Aerosols. The MacMillan Company. New York 1964.

43. Ingebo, R. Drag Coefficients for Droplets and Solid Spheres in Clouds Accelerating in Airstreams. NACA Technical Note 3762. 1956.

44. Green, H. L. and W. R. Lane. Particulate Clouds: Dusts, Smokes and Mists. Spon, England. 1964.

45. Davies, C. N., Editor. Aerosol Science. Academic Press, New York. 1966.

46. Davies, C. N. Air Filtration, Academic Press, London and New York. 1973.

47. Billings, C. E., and J. E. Wilder. Handbook of Fabric Filter Technology. Volume 1. Fabric Filter Systems Study, GCA/Technology Division. Department A, Clearinghouse, U.S. Department of Commerce, Springfield, Va. 22151. Report Number GCA-TR-70-17-G, APTD-0690. Contract CPA-22-69-38. PB-200-648. December 1970.

48. Oglesby, Sabert, Jr. and Grady B. Nichols. A Manual of Electrostatic Precipitator Technology. Part 2: Application Areas. Southern Research Institute, Birmingham, Alabama. August 25, 1970.

49. Weast, R. C. Standard Mathematical Tables. Chemical Rubber Co. Cleveland, Ohio. 1968.

50. Stober, W. A Note on the Aerodynamic Diameter and Mobility of Nonspherical Aerosol Particles. J Aerosol Sci. 2:453-456. 1971.